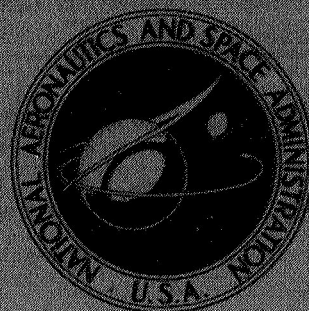


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AN EXPERIMENTAL INVESTIGATION OF COMPENSATORY AND PURSUIT TRACKING DISPLAYS WITH RATE AND ACCELERATION CONTROL DYNAMICS AND A DISTURBANCE INPUT

by *R. W. Allen and H. R. Jex*

Prepared by
SYSTEMS TECHNOLOGY, INC.
Hawthorne, Calif.
for Ames Research Center

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ABSTRACT

Four instrument-rated pilots were trained and tested with a series of different tracking displays and controlled element dynamics to validate some anomalous previous experiments and to provide a sounder data base for a theory of manual control displays.

Quasi-random (sum of 9 sinusoids) inputs were used. Compensatory (C) and pursuit (P) display modes were investigated along with a hybrid "pursuit-plus-disturbance" (P+D) display mode. For P+D the command input was displayed conventionally, while a separate, uncorrelated disturbance input was applied to the controlled element.

Rate control (K/s) and acceleration control (K/s^2) dynamics were investigated. Measurements presented include: error performance $|e|$, remnant content, control activity $|c|$, open- and closed-loop describing functions (error/input, output/error, and output/command), and subjective assessments of task difficulty. Data from the lengthy training sessions and two main-experiment sessions are presented separately. Analyses of variance were performed on the error and control scores, and on the magnitude and phase of the error/input describing function at each frequency.

The training data shows that all pilots learned quickly to perform about equally well with all displays when controlling rate dynamics. With acceleration dynamics they took much longer to learn and the results showed more variability. In the main experiment, the error performance was not sensitive to display mode, while the describing function data showed that differences in the pilot's behavior did occur, with opposing effects leading to the constant net error. The independent disturbance input proved that a compensatory loop closure does exist during pursuit tracking and that its closure parameters may be different from the purely compensatory display case.

No attempts were made to mathematically model these data, pending completion of other experiments with varying input predictability.

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SECTION I

INTRODUCTION

This research covers the first portion of an experimental program aimed at providing some of the missing gaps in the data base required for a systems analysis theory of manual control displays (Refs. 1 and 2).

There are several practical reasons for obtaining a better quantitative understanding of the human operator's behavior in pursuit situations. These include the following:

- In tasks where the external reference is present (e.g., VFR approach and landing), a pursuit model may be an appropriate representation for the human's operation.
- For director (as opposed to null steering) displays in IFR operations, the type of behavior desired and the appropriate pilot model correspond to those of the pursuit situation.
- As hypothesized by the Successive Organization of Perception (SOP) sequence (Ref. 3), a pursuit mode of response by the operator is an interim phase in the development of exceptional skill. In this hypothesis, pursuit behavior will occur both in the progression toward higher skills and in the regression to lower levels (compensatory) under stress.
- In different past investigations, pursuit and compensatory displays have both shown superior performance with different controlled elements and inputs. A quantitatively validated and efficient model is required which will explain these results and reliably predict display performance in new situations and for synthesis of improved displays.

The objectives of the pursuit tracking experiment reported herein were to:

- Prove out the new equipment, experimental techniques and procedures, and train several instrument-rated pilot subjects for use in subsequent control display research.

- Tie in the present conditions and results with past pursuit tracking results, and validate suspected anomalies in past data (based on only one subject) by using several pilot subjects.
- Explore the influence of an independent disturbance input, and use it to make direct measurements of the compensatory loop of a pursuit tracking situation.

In the light of the above purposes, this first group of experiments has been termed the "pursuit-validation" series. A second series of experiments is planned with the aim of understanding how the pilot interprets the displayed input command. Consequently, no formal mathematical modeling or data fitting has been attempted herein.

This report is arranged as follows: Section II discusses the basic compensatory and pursuit display utilization concepts under investigation and reviews some key past experiments, Section III describes the experimental setup and procedures, Section IV presents and discusses the experimental data and results, and Section V includes the conclusions and recommendations. Three Appendices contain details of the procedures and data analysis.

SECTION II

BACKGROUND

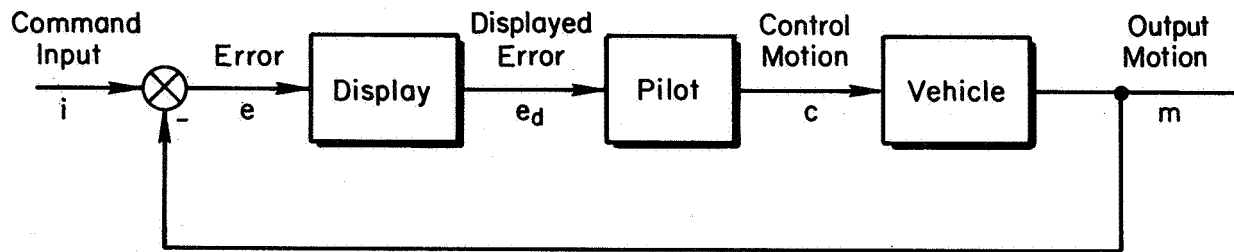
A. DISPLAY UTILIZATION CONCEPTS

1. Display Modes

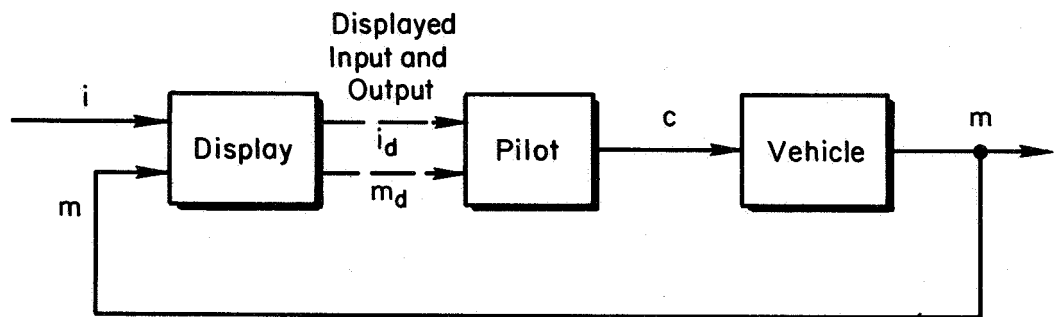
The three types of display situations to be investigated here are defined in Figure 1. With a compensatory display, only the system error, e , is available as a stimulus for operator control action, c , whereas with a pursuit display the command input, i , and the motion output, m , are separately displayed. However, presentation of both i and m signals does not necessarily imply that the pilot acts on both of them independently. For instance, with a pursuit display the operator may act only on the perceived error between i and m , thereby behaving in a compensatory manner. Thus we draw an important distinction between a pursuit display situation and the adoption of pursuit behavior by the pilot. Without resort to a preconceived mathematical model, pursuit behavior can be generally defined as the pilot's utilization of more than just the perceived error between the displayed input and output signals, and in particular, his operations in predicting and utilizing the input.

A display continuum between compensatory and pursuit modes can be functionally represented as shown in Fig. 1c. The disturbance output $d(t)$ is only displayed through the total output signal $m'(t)$, whereas the command input $i(t)$ is independently displayed to the pilot.

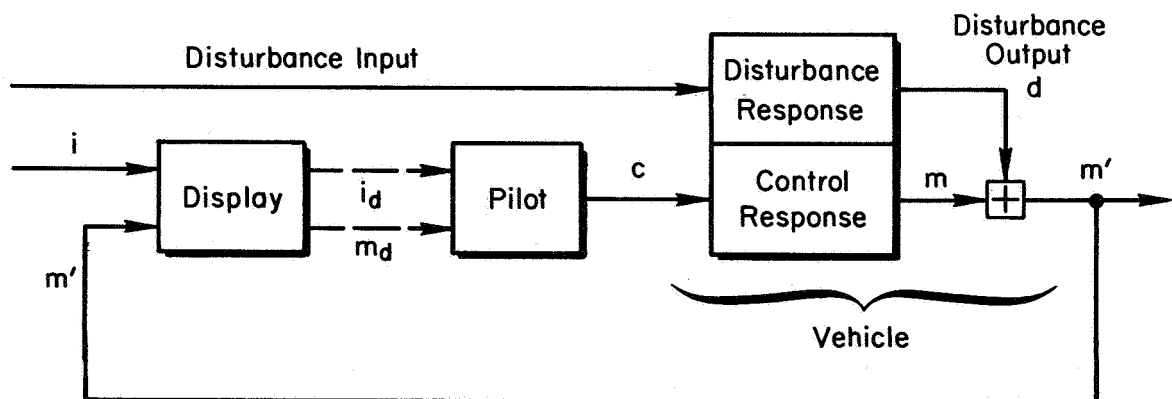
If the command input is zero or constant, then it appears as part of the display null reference. The display then becomes compensatory because the pilot can only see the total output $m'(t)$ which is the sum of the vehicle's response to the disturbance input and the controlled element's response to his control action. Conversely, when the disturbance is zero, $i(t)$ and $m(t)$ are displayed independently of each other giving a pure pursuit display. The continuum between compensatory and pursuit displays results from mixing both command and disturbance



a) Compensatory Display (C)



b) Pursuit Display (P)



c) Pursuit Display with Disturbance Input (P+D)

Figure 1. Functional Representation of Display Modes

inputs in various proportions. This situation is hereafter referred to as the pursuit-plus-disturbance display mode.

In practice the pursuit-plus-disturbance display of Fig. 1c is more common than the pure-pursuit situation of Fig. 1b. For example, with a flight director steering display, atmospheric disturbances will affect aircraft path motions, which would be displayed to the pilot via the output symbol, independently of the required steering trajectory or command input.

The command and disturbance input scheme is important experimentally as an aid to measuring and modeling the human operator. If the two inputs are statistically independent, then two independent describing functions can be computed for the human operator's response to i and d inputs, or some combination thereof. Given a pursuit display plus his perceptual processes, the pilot potentially has three or four quantities available on which to operate, i.e., i and m (displayed), and e (perceived), and possibly c (proprioceptively sensed). It is not possible to uniquely define four describing functions unless four independent inputs and outputs, each measurable by the experimenter, are available. Since perceived e and c signals are not available for measurement, only two describing functions can be uniquely separated. (Further discussion of this point is given in Ref. 8.).

In the past, only one input was used in pursuit display investigations, so the pilot operations on i , m , or e had to be inferred. Because of its practical relevance, usefulness in measurement, and lack of previous experiments of this type, the pursuit-plus-disturbance display mode was one of the key situations investigated here.

2. Pilot Behavior

Pursuit behavior differs from compensatory behavior when the pilot makes some use of the additional information provided by the pursuit display over that provided by the compensatory display. Table I presents the possible combinations of input, disturbance, display mode, and type of pilot behavior. Depending on the relative size of the command versus disturbance inputs, it is possible for an actual pursuit display situation

TABLE I

MATRIX OF PILOT MODELS FOR PURSUIT DISPLAY SITUATIONS

Legend: D = Effective display situation σ_i = rms input
 B = Level of pilot's display utilization behavior σ_d = rms disturbance referenced to the display
 E = Experimental status (describing functions) σ_r = rms remnant

INPUT LEVEL	DISTURBANCE LEVEL		
	a. Zero ($\sigma_d = 0$)	b. Small ($\sigma_d \ll \sigma_i$)	c. Large ($\sigma_d \geq \sigma_i$)
1. Zero ($\sigma_i = 0$)	D. Compensatory B. Compensatory regulation against remnant E. (Model not directly measurable)	D. Compensatory B. Compensatory E. Done and models available (Refs. 1,3)	D. Compensatory B. Compensatory E. Done and models available
2. Small ($\sigma_i \leq \sigma_r$)	D. Pure Pursuit B. Pursuit or Compensatory (?) E. No data available	D. Pursuit-plus-Disturbance B. (Unknown) E. No data available	D. Pursuit-plus-Disturbance or Compensatory with small display noise B. Compensatory if target motions are very small E. No data available
3. Large ($\sigma_i \gg \sigma_r$)	D. Pure Pursuit B. Pursuit but with some questions E. Some data, some anomalies	D. Perceptually Pure Pursuit B. Pursuit, if anomalies are resolved for $\sigma_d=0$ E. No data available	D. Pursuit-plus-Disturbance B. (Unknown) E. No data available

to elicit either pursuit or compensatory pilot behavior, as noted previously. In addition, it is possible for the pilot to exhibit either pursuit or compensatory behavior for many of the conditions listed in Table I. Thus there are four possibilities—two kinds of behavior for both compensatory and pursuit displays. Actually, by considering only random-appearing inputs, we have eliminated pursuit behavior for compensatory displays. A brief discussion of the status of knowledge about behavior for the various combinations in Table I is given below.

- a. Compensatory task and compensatory behavior (σ_d present with $\sigma_i = 0$). The compensatory display situation has been extensively studied and analyzed (Refs. 4 and 6) for small and large σ_d . For $Y_c = K_c/(s-\lambda)$, Ref. 7 studied the effects on the pilot's describing function as $\sigma_d \rightarrow 0$ and found that the pilot's describing function is essentially unchanged down to very small values of σ_d . This was used to infer Y_p in the unmeasurable condition $\sigma_d = 0$.
- b. Pure Pursuit task and either pursuit or compensatory behavior (σ_i present with $\sigma_d = 0$). The pursuit situation received some attention in Ref. 4 and was extensively studied in Ref. 8. It was found that the provision of a pursuit display does not always result in distinct pursuit behavior. Reference 8 contains a procedure for detecting the presence of pursuit behavior, and also implying some of the properties of the pilot's behavior although direct measurement of the pilot's describing functions was not possible.
- c. Perceptually Pure Pursuit (σ_i large, σ_d small). With this configuration we can measure all of the pilot's describing functions. However, the inclusion of the disturbance input, d , in the pursuit behavior situation changes the pilot's task and may also change his describing functions. It should be possible to find a σ_d small enough not to affect the pilot's behavior, yet large enough to enable independent measurements to be taken. An experiment of this type was performed here.
- d. Pursuit Plus Disturbance (σ_i and σ_d of same order). These experiments have not been performed, so no assertions of pilot behavior are possible as yet.

B. IMPLICATIONS OF PREVIOUS EXPERIMENTS

Considerable experimental work has been done on the compensatory versus pursuit display question. The more pertinent studies have been reviewed by Wasicko, et al., in Ref. 8. Several interesting conclusions can be drawn by distilling the performance data from these studies (as summarized in Table I of Ref. 8) into the form shown in Table II. The "best" performing display, from the standpoint of minimum tracking error score, is shown versus controlled element dynamics for both "predictable" and "unpredictable" command inputs.* The conclusions drawn from Table II are:

- The great majority of past investigators used pure-gain dynamics ($Y_c = K$) for their comparisons.
- With pure-gain dynamics, a pursuit display always gave equal or superior performance to a compensatory display.
- The two experiments for other dynamics (Refs. 9, 10) show anomalous results in that the compensatory display was sometimes superior to the pursuit case with no consistent trend as a function of controlled element difficulty.
- There are only two experiments with describing function measurements.
- Only one investigation gives performance and describing function data for more than one controlled element, and this was all on one human operator subject.

Thus, it was felt necessary to recheck, with more subjects, the anomalous cases uncovered in past data. Also, because different learning rates

*As used here, somewhat arbitrarily: "Predictable" means having low, or narrowband, frequency content and sharp cutoff characteristics, with no power near the normal crossover frequency range of 0.5 to 1.0 Hz (e.g., single sinusoids of < 1.0 Hz and sums of 2 to 3 sinusoids of frequency < 0.5 Hz); "Unpredictable" means having a high bandwidth, and with perceivable power near the crossover region (e.g., sums of 4 or more sinusoids, filtered noise, etc.).

TABLE II

SUPERIORITY OF PURSUIT VERSUS COMPENSATORY DISPLAY PERFORMANCE IN PAST EXPERIMENTS
(Based on Tables I and IV of Ref. 8)

SOURCE (Reference No.)	DESCRIBING FUNCTION MEASUREMENTS	CONTROLLED ELEMENT							
		$Y_C = K_C$		$Y_C = K/s$		$Y_C = K/s^2$		$Y_C = K/s(s-1.5)$	
		Input:		Input:		Input:		Input:	
		Pred.	Unpred.	Pred.	Unpred.	Pred.	Unpred.	Pred.	Unpred.
Chernikoff, Birmingham, and Taylor (9)	No	P	—	—	—	—	—	—	—
Chernikoff and Taylor (10)	No	Slow i: P	Fast i: P	—	—	—	—	—	—
Senders and Cruzen (11)	No	P	—	—	—	—	—	—	—
Poulton (12)	No	P	P	—	—	—	—	—	—
Walston and Warren (13)	No	P	P	—	—	—	—	—	—
Obermeyer, Swartz, and Muckler (14)	No	P ÷ C	P	C	P	C	C	—	—
Hartman (15, 16)	No	—	P	—	—	—	—	—	—
Elkind (4)	Yes	—	P	—	—	—	—	—	—
Wasicko, McRuer, and Magdaleno (8)	Yes	—	P	—	C	—	P	P	P

Note: Letter shows display mode yielding best performance (lowest error score).
C = compensatory, P = pursuit

could have led to some of the past inconsistencies, each subject should receive thorough training and monitoring.

Close examination of the performance and describing function plots presented by Wasicko, et al., in Ref. 8 reveals an important complication in comparing pursuit and compensatory displays. The tracking error is composed of a "coherent" portion due to errors in tracking the command and a "remnant" portion, which results from random variations introduced by the operator. It is possible that a pursuit display may permit reduction of one component at the expense of the other, yielding no net improvement. This was actually the case in Ref. 8 for K/s^2 dynamics and an input bandwidth of $\omega_i = 2.5$ rad/sec, where the pursuit display yielded lower coherent error but larger remnant error for a net near-equality of performance.

Describing functions are a more sensitive indicator of the pilot's behavior than error scores. If the variation of the describing function and remnant parameters with the pursuit task variables can be established, then the performance anomalies could be explained and predicted.

The describing function between system output and system error, $Y_\beta(j\omega) = M(j\omega)/E(j\omega)$, was used in Ref. 8 to measure the dynamic effects of compensatory versus pursuit display presentation. For the compensatory display Y_β is equal to the open-loop describing function, while for the pursuit display it represents an equivalent system open-loop describing function. A summary of qualitative trends in Y_β from Ref. 8 and pertinent to the present study is given below:

$Y_c = K_c$ The pursuit display induced greater low- and mid-frequency gain, which agrees with the increased control activity for pursuit cases also observed in the data. The pursuit display yielded less mid-frequency phase lag.

$Y_c = K_c/s$ Less low frequency phase and lower mid-frequency gain resulted from pursuit display.

$Y_c = K_c/s^2$ The pursuit display yielded less phase lag in the low- and mid-frequency ranges. In addition, the mid- and high-frequency gains were less for the pursuit display.

The above study by Wasicko, et al., included a wide range of experimental conditions but was limited in that only one subject was used and pursuit-plus-disturbance inputs were not employed. An attempt was made at fitting a particular pursuit model (the "implied pursuit" model, which assumes that the compensatory operations are identical in both display modes). However the resulting estimates of the pursuit operation describing function were highly variable with a form more complex than a simple inversion of the controlled element, as predicted by the theory therein. In light of the above discussion, emphasis here was placed on thoroughly investigating K/s and K/s^2 dynamics and on exploring the use of a small, separate disturbance input to validate the adoption of compensatory behavior by the pilot during pursuit display situations.

SECTION III

EXPERIMENTAL SETUP AND PROCEDURES

A. EXPERIMENTAL DESIGN

In order to best achieve the objectives set down for this study, careful attention was paid to the design of the experiment and the procedures used in conducting it. To obtain as much information as possible, the experiment was organized into a "training" phase and a "main experiment" phase.

The variables of interest in the training phase are listed in Table III. The objectives of the training phase were (1) to train the subjects to asymptotic levels of performance and response behavior, (2) to determine the effect of display mode on skill acquisition, and (3) to determine the effect of training on response behavior (describing function measurements).

TABLE III

TRAINING PHASE VARIABLES

- | |
|---|
| A. Subjects: 4 |
| B. Display Mode: |
| 1. Compensatory |
| 2. Pursuit |
| C. Controlled Element |
| 1. $Y_c = K/s$ |
| 2. $Y_c = K/s^2$ |
| D. Order of Presentation of Display Mode: |
| 1. Compensatory \rightarrow Pursuit |
| 2. Pursuit \rightarrow Compensatory |

The design of the training phase experiment is shown in Table IV. The design was set up so that a subject would use the same display exclusively in session one and the first part of session two, and then switch to the alternate display for the remainder of session two. In this manner some information could be gained on the degree of learning obtained with a particular display, and the amount of transfer of learning achieved when switching to the alternate display. The final training sessions were designed to equalize the subjects' skill on both displays.

More practice runs were devoted to the K/s^2 controlled element because of its difficulty and because experience has shown that longer periods of practice are required to reach asymptotic behavior with these dynamics.

TABLE IV
EXPERIMENTAL DESIGN FOR TRAINING SESSIONS

		ORDER OF PRESENTATION									
Session		1		2				3 and 4			
Subjects 1 and 2	Display	Comp.		Comp.		Purs.		Purs.	Comp.	Purs.	Comp.
	Dynamics	K/s	K/s^2	K/s	K/s^2	K/s	K/s^2	K/s	K/s	K/s^2	K/s^2
	No. of Trials	6	9	3	3	6	9	3	3	6	6
Subjects 3 and 4	Display	Purs.		Purs.		Comp.		Comp.	Purs.	Comp.	Purs.
	Dynamics	K/s	K/s^2	K/s	K/s^2	K/s	K/s^2	K/s	K/s	K/s^2	K/s^2
	No. of Trials	6	9	3	3	6	9	3	3	6	6

The design of the main experiment is shown in Fig. 2. Disturbance inputs were added to the display variable and the experiment was duplicated on each of two days in order to account for any further learning effects. So as to simplify applying analysis of variance techniques to the data, the experiment was organized as a complete factorial design.

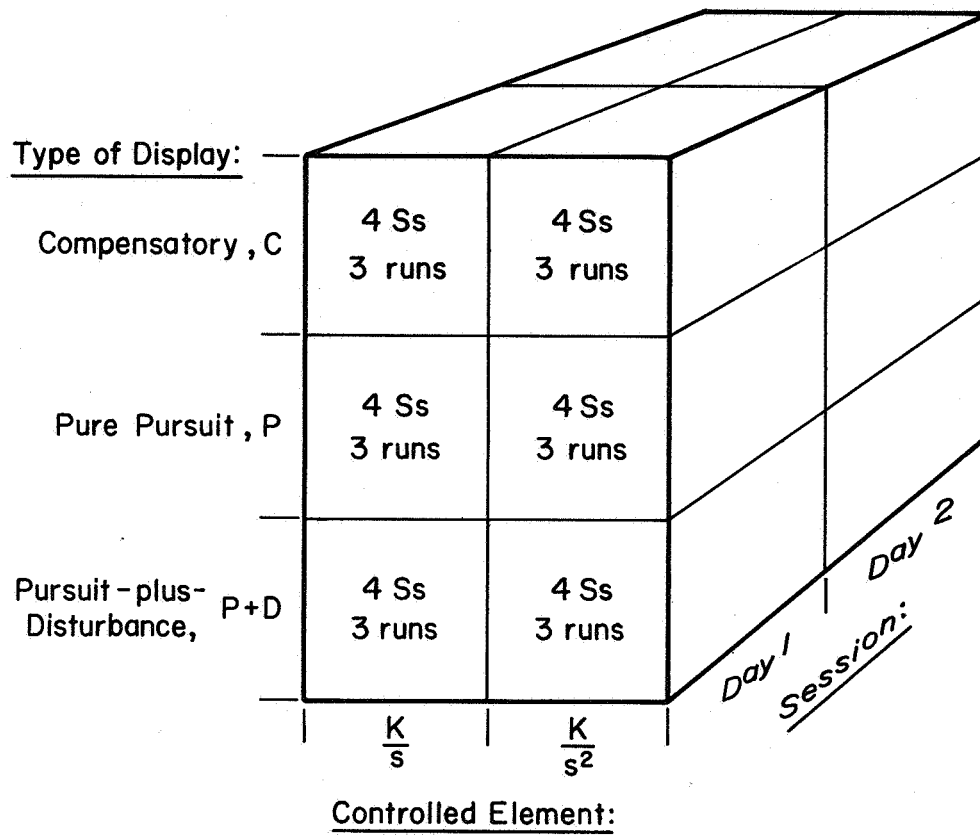


Figure 2. Design of the Main Experiment

B. EXPERIMENTAL SETUP

A photograph of the tracking setup is given in Fig. 3. Block diagrams of the experimental display configurations are illustrated in Fig. 4, along with the display presentations as they appeared on the CRT. The compensatory and pure pursuit configurations were used during training, and the pursuit-plus-disturbance configuration was added for the main experiment.

Input command (i) and disturbance (d) signals were composed of nine sine waves. The command and disturbance spectra are shown in Fig. 5, and the frequencies of the various waves are given in Table V. Following the code used by Elkind, Ref. 4, and McRuer, et al., Ref. 17, this input is designated as B6-3.2-1cm (-20 dB shelf; 3.2 rad/sec dominant input "bandwidth;" 1 cm rms level).

TABLE V
INPUT FREQUENCIES

SINE WAVE COMPONENT	ω_i (RAD/SEC)	f_i (Hz)	HARMONICS		n FOR 100 SEC TRIAL
			$2f_i$	$3f_i$	
1	0.3142	0.05	0.10	0.15	5
2	0.5027*	0.08	0.16	0.24	8
3	0.7540	0.12	0.24	0.36	12
4	1.1938*	0.19	0.38	0.57	19
5	1.9478	0.31	0.62	0.93	31
6	3.2044*	0.51	1.02	1.53	51
7	5.1522*	0.82	1.64	2.46	82
8	8.2310	1.31	2.62	3.93	131
9	13.1319	2.09	4.18	6.27	209

*Describing functions measured on-line.

As shown in Fig. 5, two components were removed from the command input to form the disturbance input during the pursuit plus disturbance tests. The low frequency disturbance component was chosen to more thoroughly examine the describing function differences between displays in this region previously observed by Wasicko, et al., (Ref. 8). The high frequency component was selected to lie close to the unity gain crossover region.

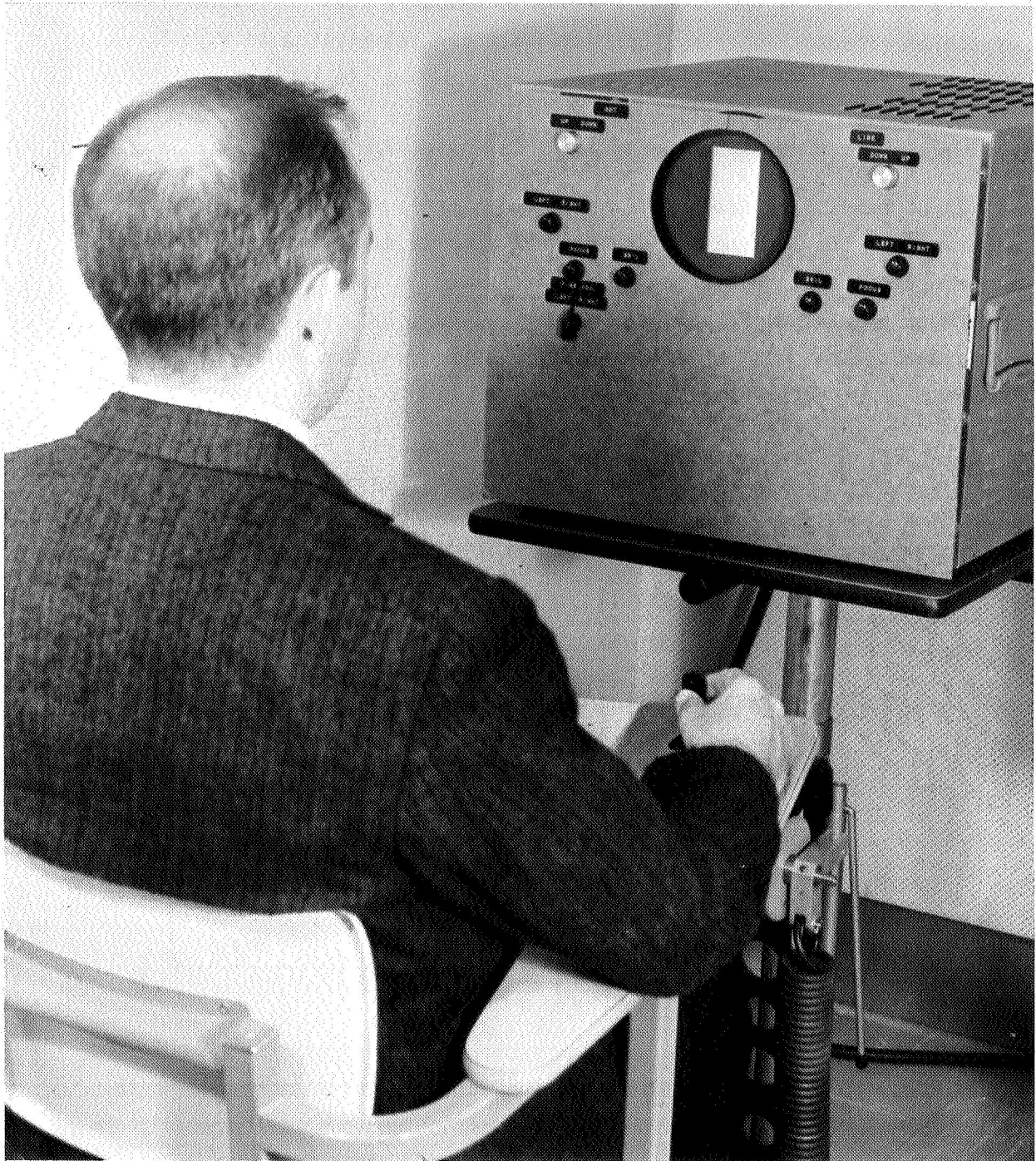
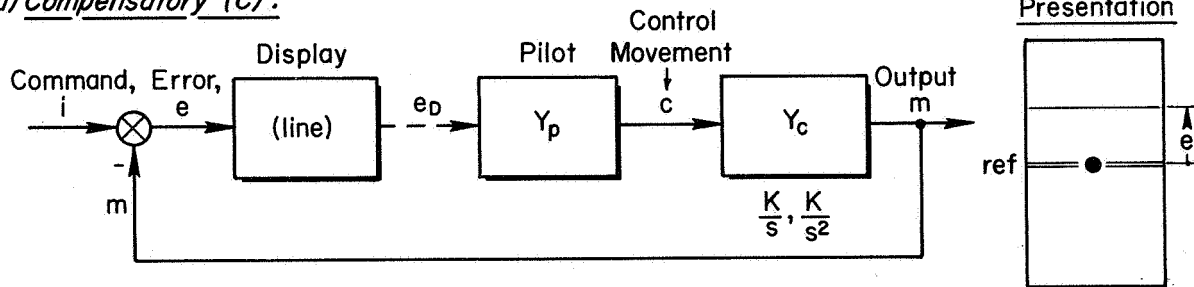


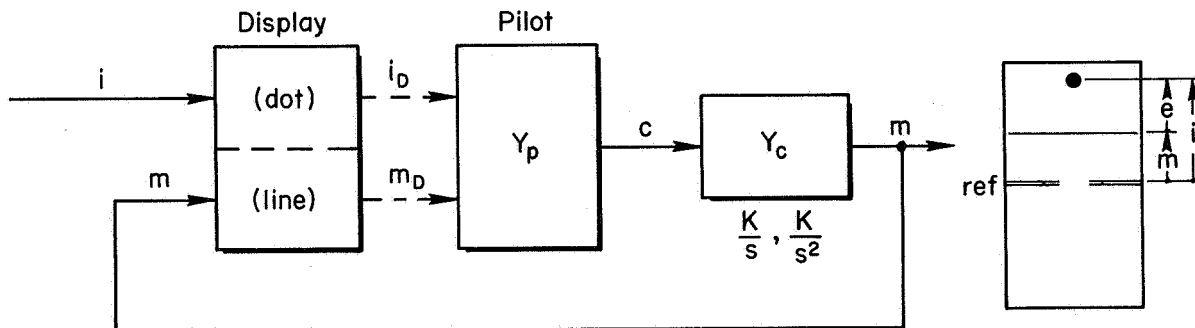
Figure 3. Overall View of Tracking Apparatus

DISPLAY CONFIGURATIONS

a) Compensatory (C):



b) Pure Pursuit (P):



c) Pursuit + Disturbance (P+D):

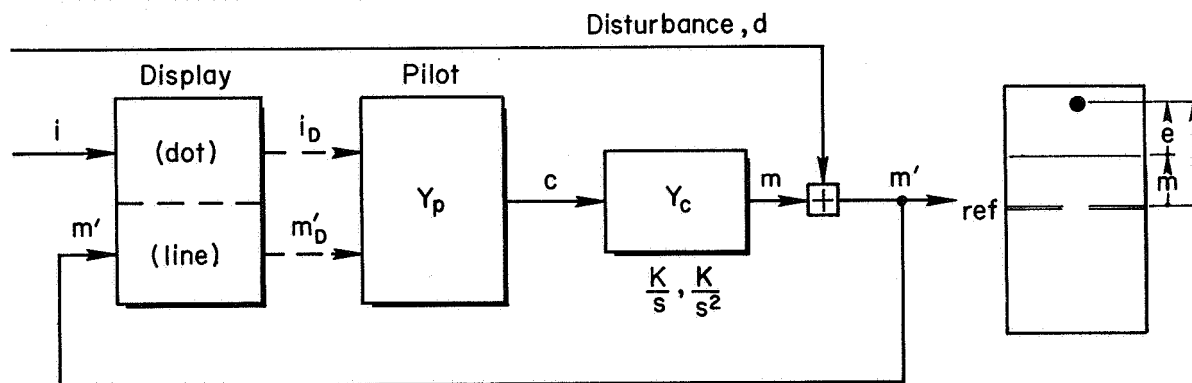
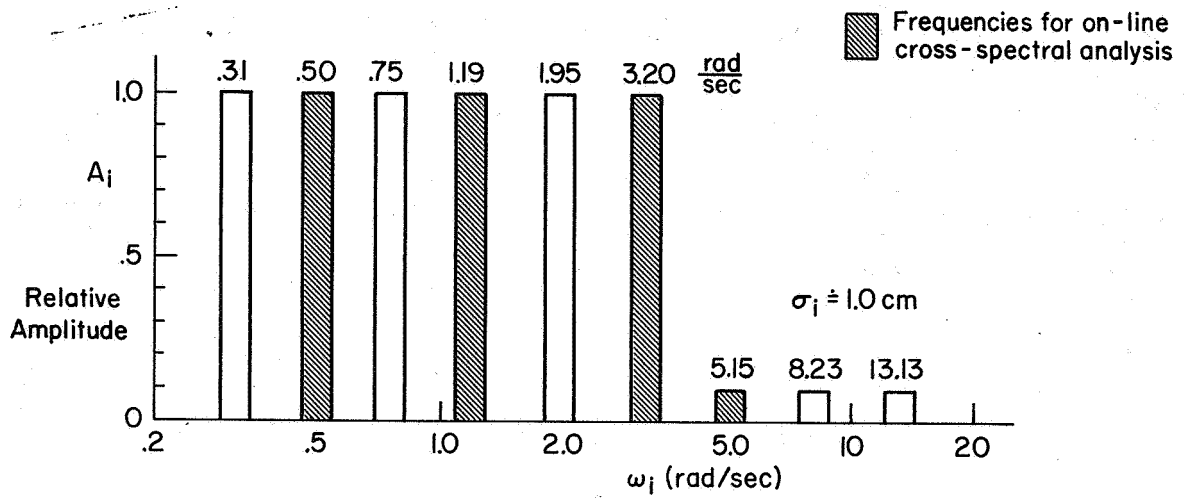
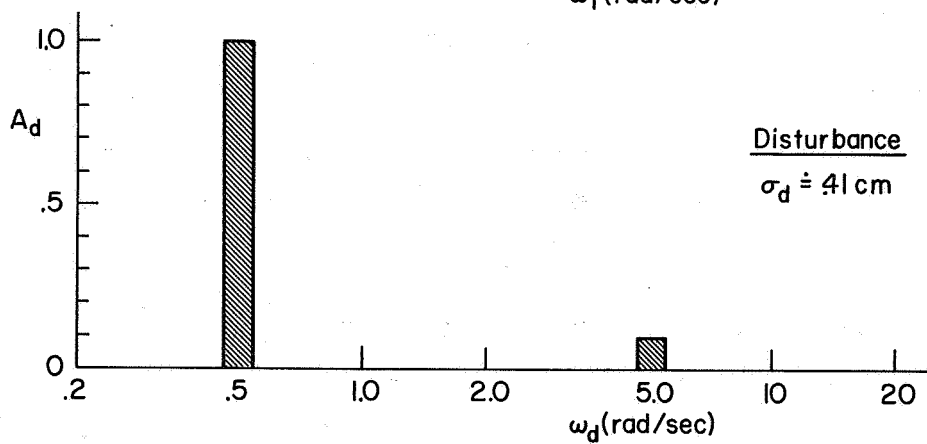
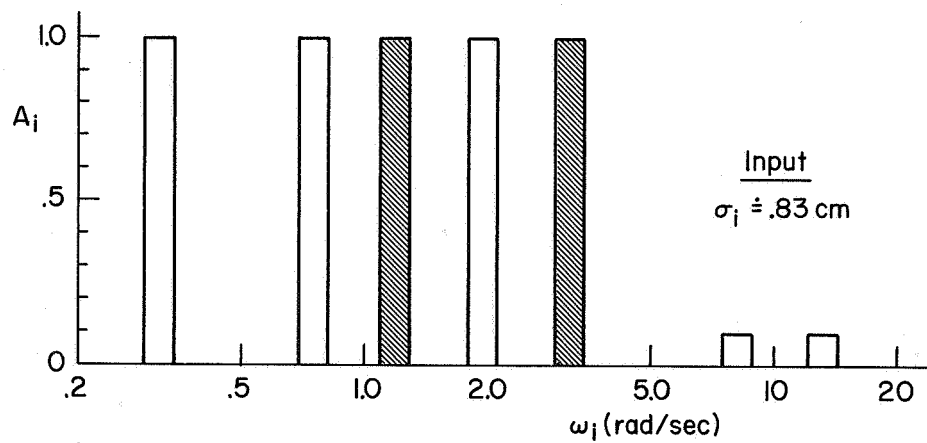


Figure 4. Functional Diagrams of Display Configurations



a) Compensatory and Pure Pursuit



b) Pursuit Plus Disturbance

Figure 5. Command and Disturbance Input Amplitude Spectra

The rms deflection of the total input forcing function (i.e., 9 sine wave components) was 1.0 cm (0.39 in.). For the pursuit plus disturbance case the command input rms deflection was 0.83 cm (0.33 in.) and the disturbance input rms deflection was 0.41 cm (0.16 in.). The viewing distance of the display was about 65 cm, giving an equivalent rms visual angle for the forcing function of approximately 1.0 deg.

The side stick controller was spring restrained and had minimal friction, viscous damping, and inertia.* The stick was most easily operated with the fingers although the subjects were not constrained to this mode of operation. The distance from the center of rotation to the reference grip position was about 14 cm (5.5 in.), and the rather stiff force gradient at this point was 10 Newtons per cm (5.71 lb/in.).

C. MEASUREMENTS

Data were measured on-line during the experiment and collected at the end of each run. Average absolute error scores and average absolute control action scores were obtained as performance measures. The error scores were normalized by dividing them by the relevant mean absolute input. Data required to compute the error-to-input describing function were obtained at the four frequencies indicated in Fig. 5 and Table V. The lowest and highest measurement frequencies also formed the disturbance input for the pursuit plus disturbance display condition. The details of describing function measurements and computations are given in Appendix A. Also outlined there is the interpolation scheme devised to calculate the portions of the error linearly correlated and uncorrelated with the input.

D. EXPERIMENTAL PROCEDURE

1. Training

The pilots were given one minute of practice prior to the first data run in order to familiarize them with the equipment and task. The data runs then followed the design shown previously in Fig. 2. Another brief practice trial preceded the first trial with K/s^2 controlled

*Stick natural frequency = 17 Hz (107 rad/sec); damping ratio = 0.25.

element dynamics. The trials lasted 120 sec, and the performance and dynamic response scores were measured over the last 100 sec. A two minute rest was given between each block of three trials and a 5 to 10 minute rest was given between changes in controlled element for Days 1, 3, and 4 and between display modes on Day 2.

The pilots were told that the task was highly idealized, but that it resembled terrain following or an instrument landing approach task in the pitch axis. The K/s controlled element was likened to a "good" (handling) aircraft and the K/s^2 case to an aircraft with sluggish handling qualities. The only performance criterion stated to the subjects was to "follow the input as closely as possible, i.e., track with minimum error." In order to motivate the subjects they were informed of their error scores as the training progressed, and also were told of the performance levels achieved in previous sessions.

2. Main Experiment

A one minute warmup run was given prior to data runs, and another warmup run was given preceding the K/s^2 trial sequence. Run length and scoring periods were the same as for the training. The K/s controlled element was always presented first in each session, and the K/s^2 conditions followed a ten minute rest period. The three display modes were presented in partially counterbalanced orderings among the four subjects and two days in order to minimize intrasession learning or fatigue effects.

E. PILOT SUBJECTS

The subjects were all instrument-rated pilots. Statistics on each of the pilots are given in Table VI. Three of the pilots were instructors and flew on a regular basis. The fourth pilot flew mainly on weekends.

The pilots were briefed on the overall display research program under which this study was conducted, and seemed highly motivated in developing the tracking skills required for this experiment.

TABLE VI

PILOT SUBJECT STATISTICS

PILOT	AGE	AERONAUTICAL RATINGS	TOTAL FLIGHT HOURS	INSTRUMENT HOURS
1	22	Commercial; Instructor; Instrument	2,200	110
2	24	Instructor; Multi-engine; Instrument	1,100	60
3	23	VFR Charter; Instructor; Multi-engine; Instrument	1,800	209
4	28	Commercial; Multi-engine; Instrument	260	57

SECTION IV

RESULTS AND DISCUSSION

A. TRAINING

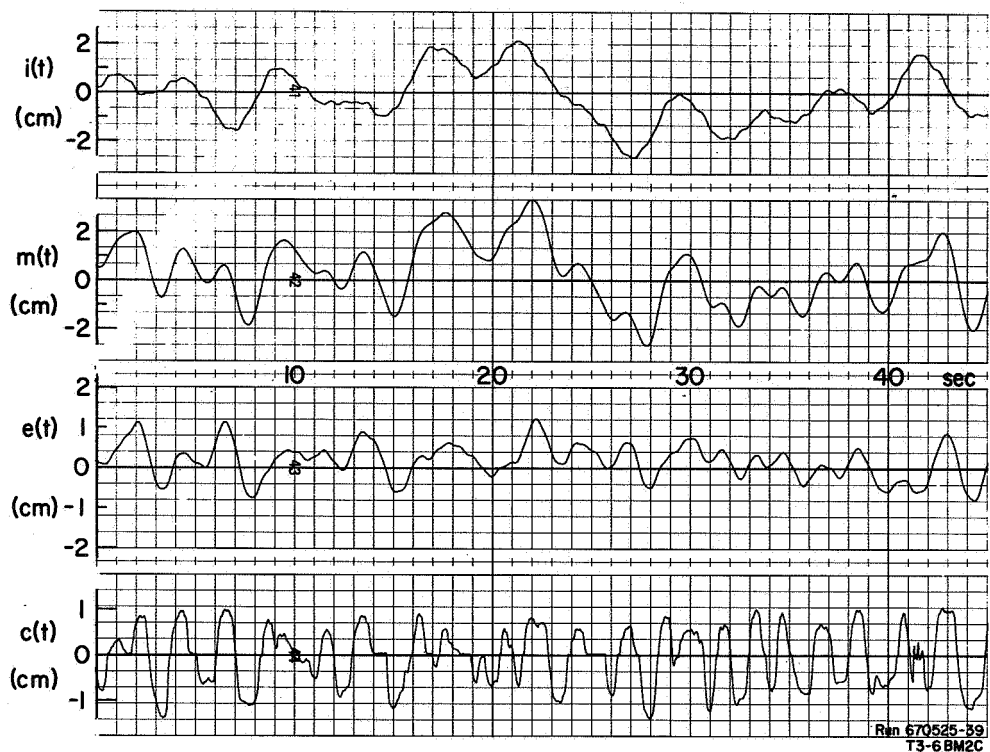
Typical time histories for runs with compensatory and pursuit displays and K/s^2 dynamics are shown in Fig. 6. Notice that the control action for the compensatory display is larger, more bang-bang, and more rapid than for the pursuit display.

Error and control scores versus training trials are shown in Figs. 7 and 8 for each subject. Both the error and control scores indicate that Subjects 1, 3, and 4 reached fairly asymptotic performance levels for all conditions. Subject 2 had some difficulty with K/s^2 dynamics, although his scores for the K/s dynamics were comparable to the others.

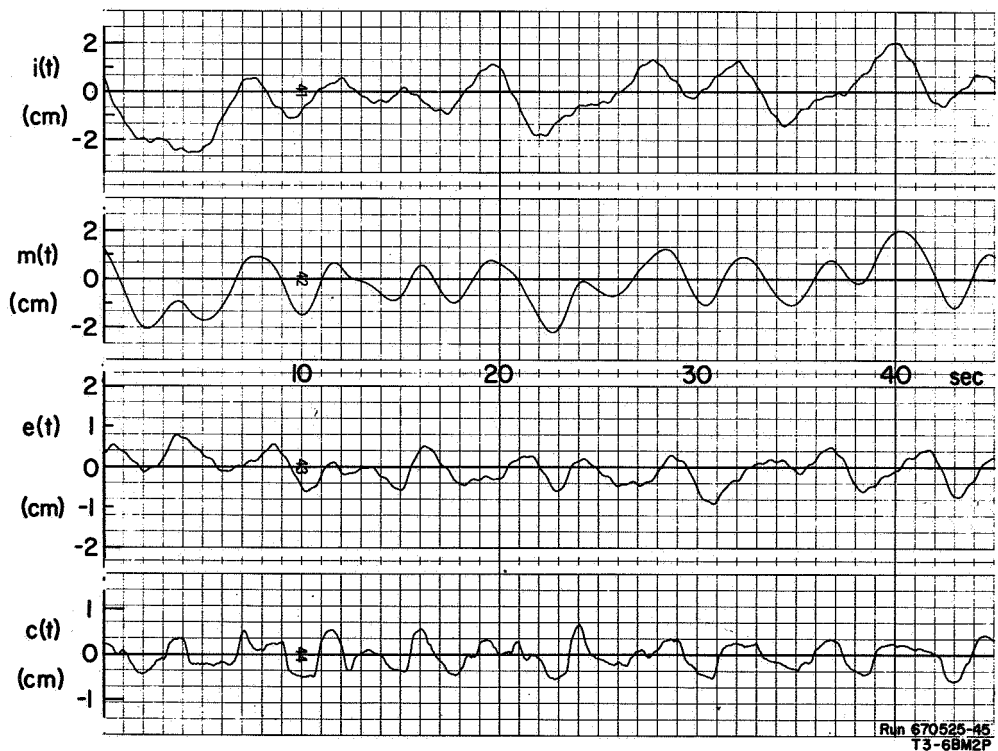
Both Subjects 3 and 4 (Fig. 7c and d) received the pursuit display mode during their first training session, and both achieved stable performance levels during the first session and consistent, asymptotic performance by the third session. These results suggest that tracking skill is achieved quicker when the subject can see the results of his controller actions independently of the forcing function as allowed by the pursuit display mode. This theory is only tentatively advanced, however, because of the small subject population involved in the training trials.

Aside from effects on learning, the performance differences between compensatory and pursuit display tracking were generally small and inconsistent among subjects. The one outstanding difference occurred in K/s^2 control scores ($|c|$). For final performance levels the K/s^2 control scores achieved with the compensatory display mode are 40 percent greater than the scores incurred in the pursuit mode; see Fig. 8, open tagged symbols.

The only training effect on describing function measurements occurred with the compensatory display mode and K/s^2 dynamics. An example of this effect is illustrated in Fig. 9 with the E/I describing function. The amplitude data show that low-frequency error performance improves with training, while the peaking at high frequencies increases. These effects reflect higher gains and lower stability margins permitted by greater pilot consistency.



a) Compensatory Display



b) Pursuit Display

Figure 6. Typical Time Histories with K/s^2 Dynamics

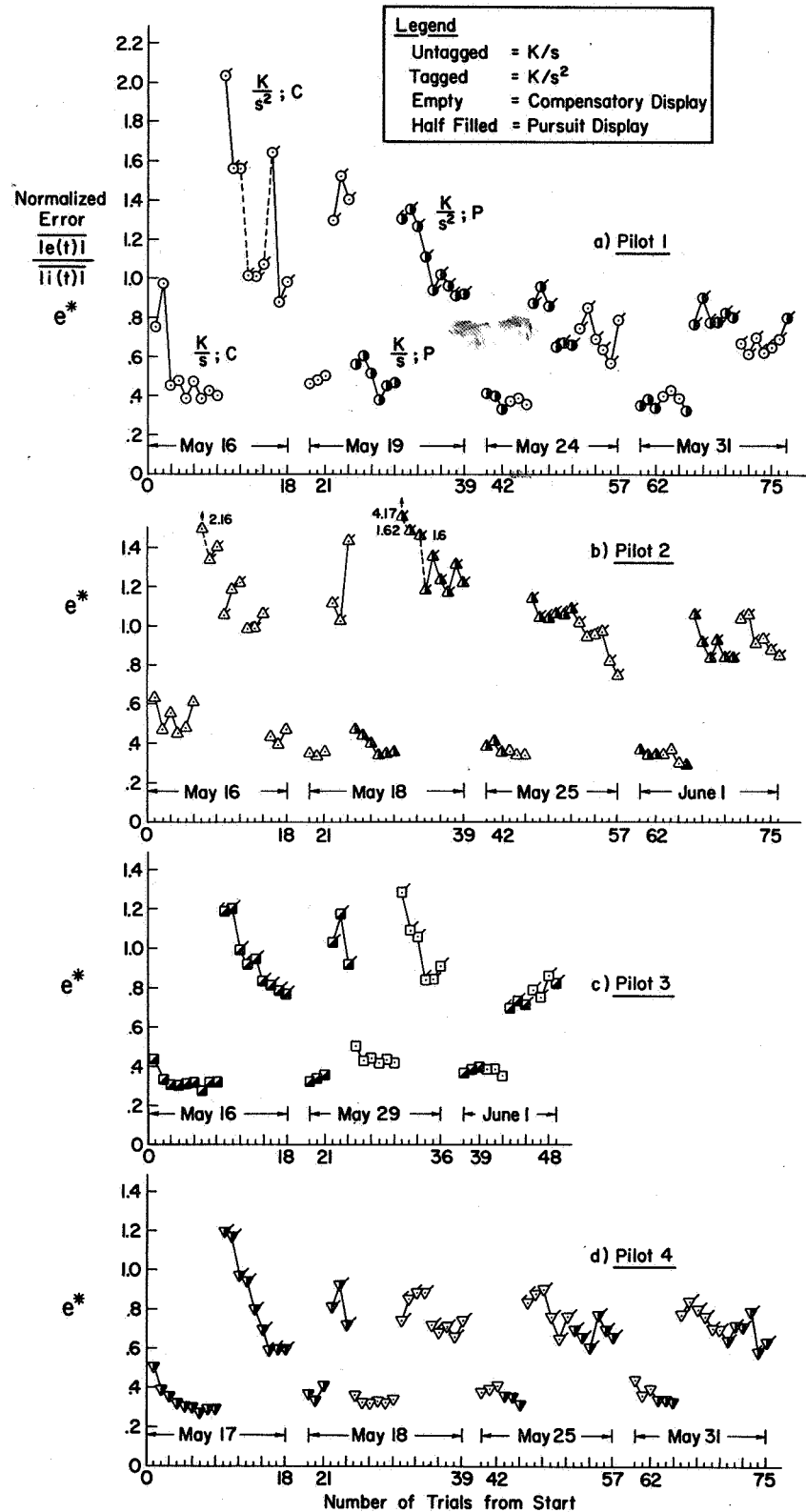


Figure 7. Normalized Error Versus Training Trials

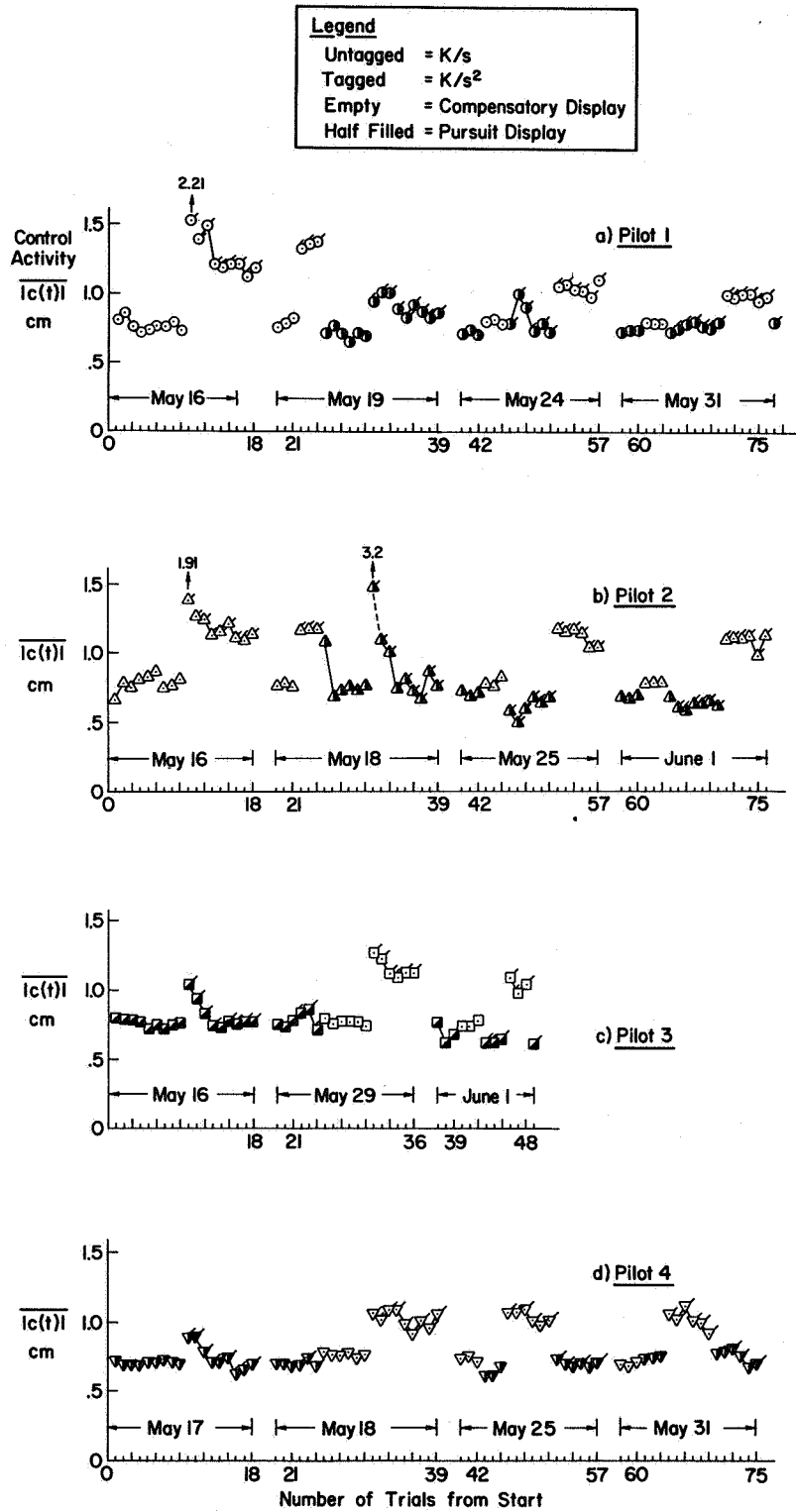
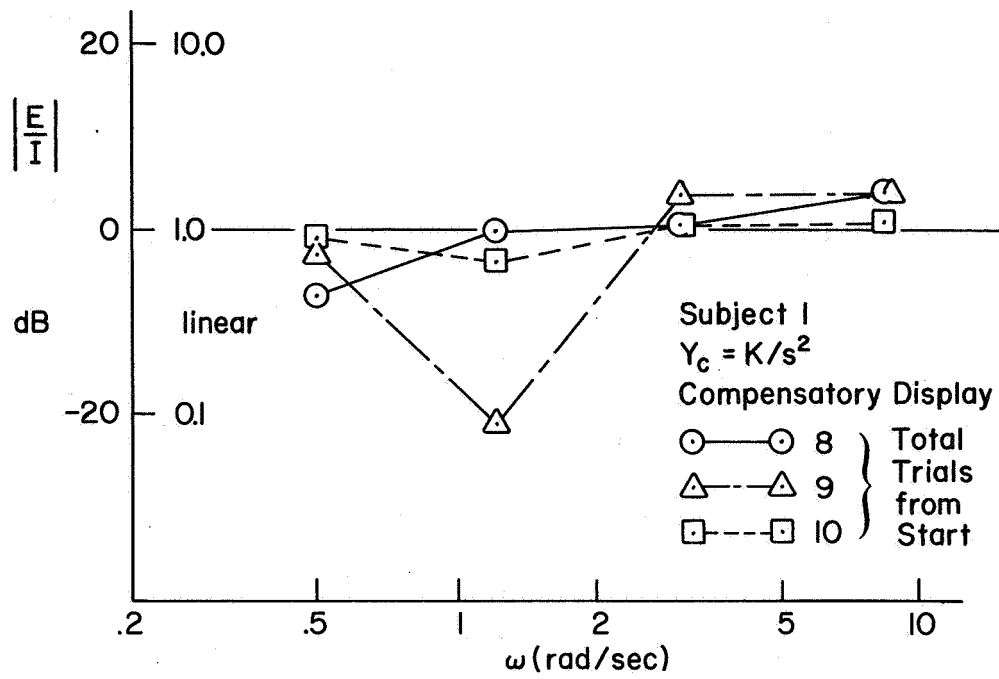
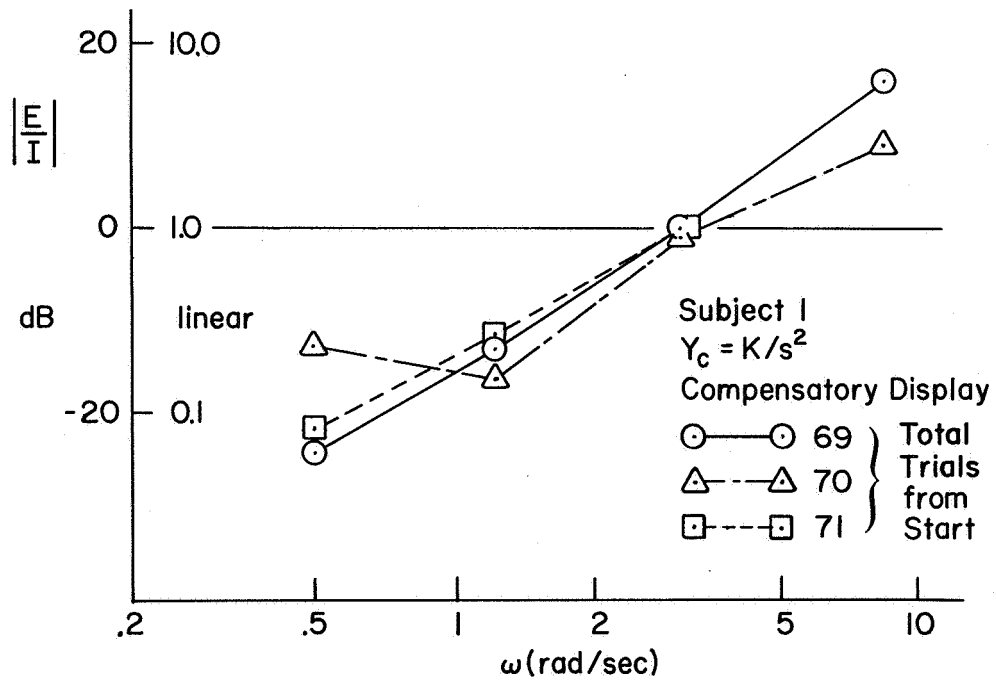


Figure 8. Control Activity Versus Training Trials



a) Session One



b) Session Four

Figure 9. Effect of Training on the Error/Input Describing Function Amplitudes with K/s^2 Dynamics

B. MAIN EXPERIMENT

1. Performance Measurements

The mean values of the normalized average absolute error scores and integrated control action scores for each cell in the main experiment (3 observations per cell) are plotted in Fig. 10. The K/s data (especially the intrasubject rankings) appear quite consistent, with the exception of Subject 1 who shows an improvement in error score between Day 1 and Day 2. The scores for K/s^2 dynamics are less consistent, and there still is some evidence of learning in Subjects 1 and 3. An interesting feature of the control scores is that, with one exception, $\overline{|c|}$ varies less among subjects, days, and even dynamics than the error scores! The exception is for the K/s^2 compensatory display case, where the increased $\overline{|c|}$ is due to the more bang-bang control action noted previously in connection with the training runs (see Fig. 6). No good reason was found for the unusual constancy of $\overline{|c|}$ in this experiment. The equality between K/s and K/s^2 dynamics results from subjectively optimizing the controlled element gain before the training runs, so it may be somewhat fortuitous. Neither the control movement nor the scoring integrator was saturated (witness the higher compensatory K/s^2 scores), and the control force levels were not excessive. It is tempting to suggest an innate "comfortable" control work rate (power $\sim F^2 \sim c^2$) but nothing in the pilot commentary was found to support this hypothesis.

Mean values for total error, the input-correlated and uncorrelated error components, and integrated control activity are plotted in Fig. 11. The interpolation scheme for computing correlated error is described in Appendix A. The data were averaged over the four subjects and the two sessions in which the main experiment was conducted.

Analysis of variance techniques (ANOV) were used to analyze the e^* , e_I^* , e_n^* , and $\overline{|c|}$ scores. The details of these analyses are given in Appendix B, and the assertions made here are based on the significant results. The residual variance shown in Fig. 11 was obtained from the ANOV.

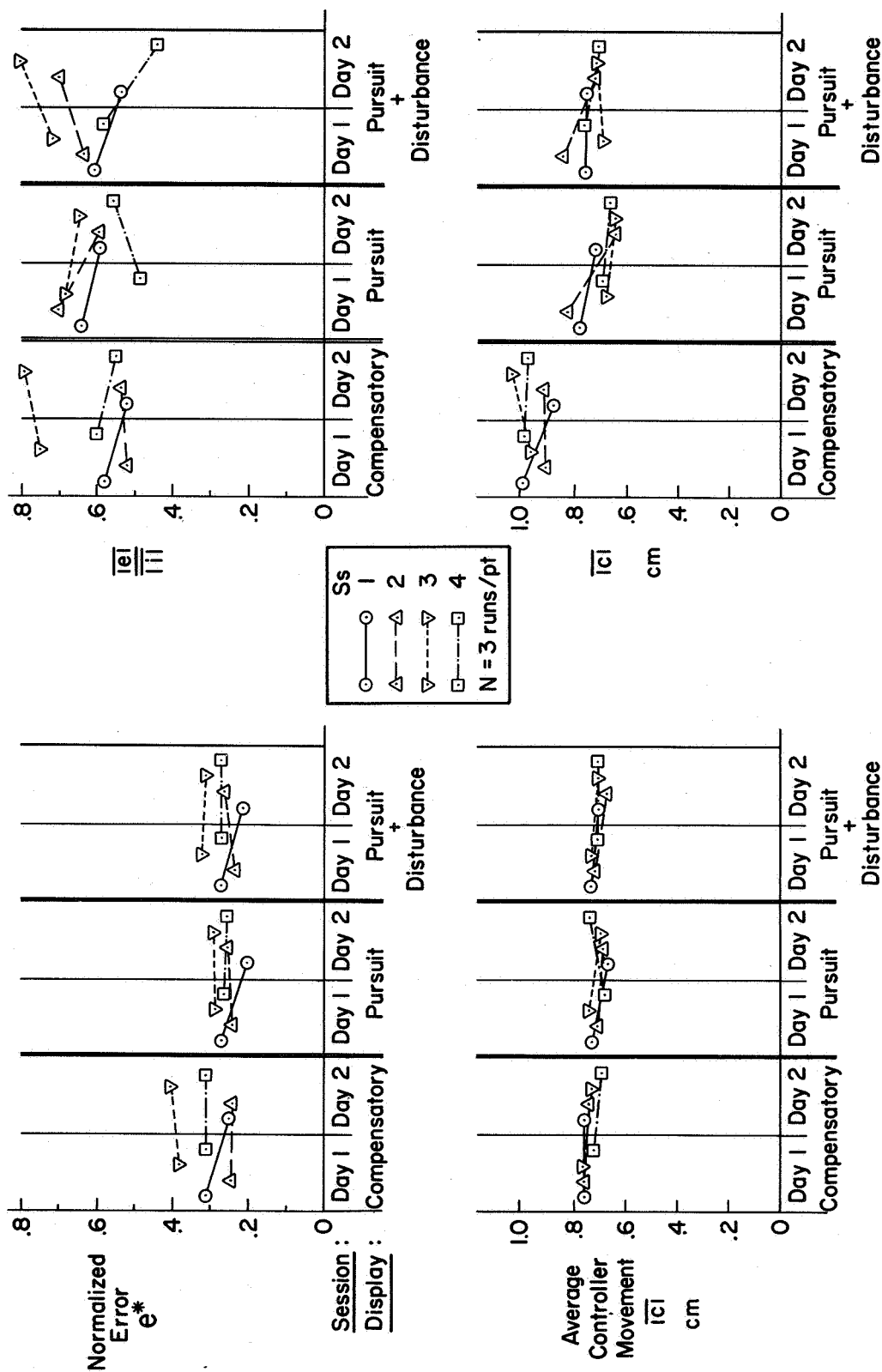


Figure 10. Averaged Normalized Error and Control Activity Versus Display, Dynamics, Session, and Subject for the Main Experiment

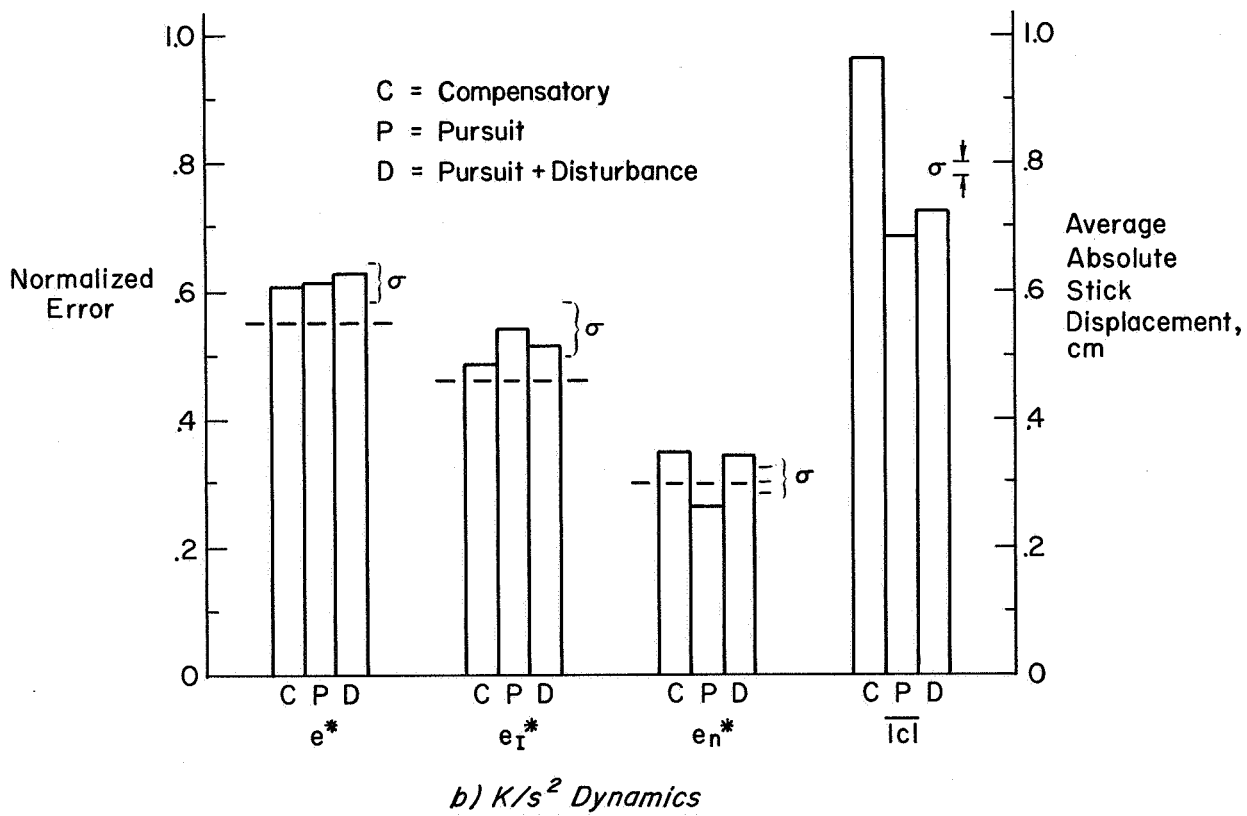
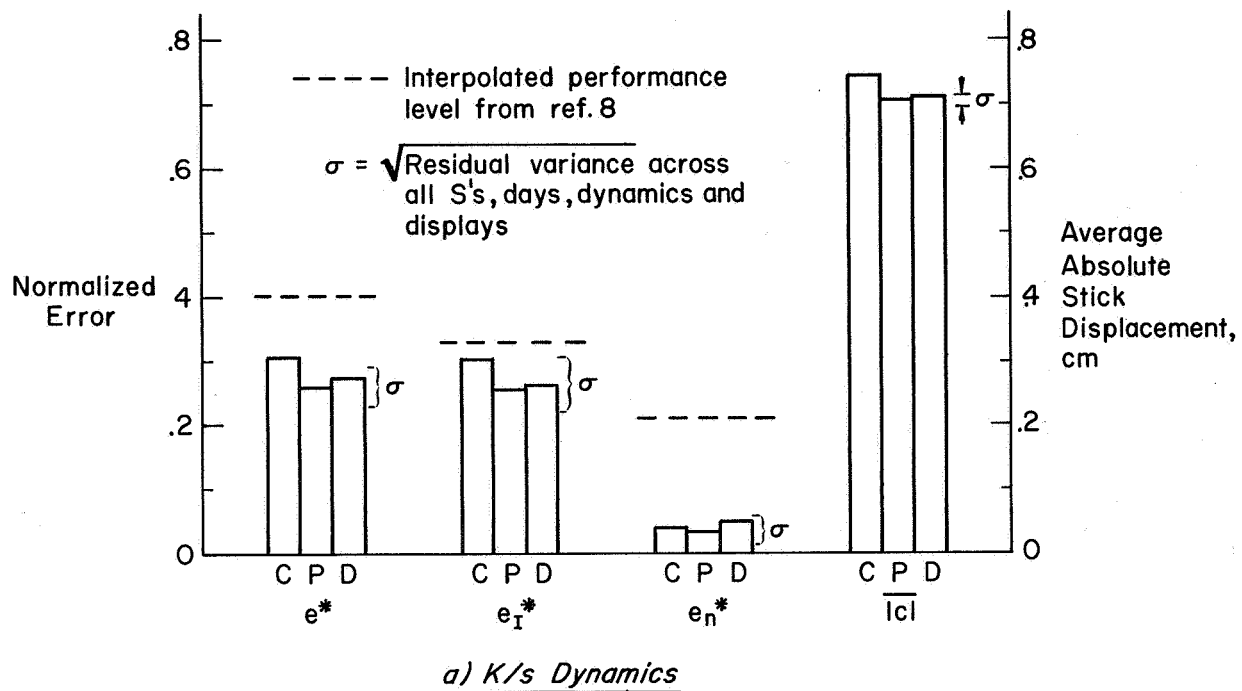


Figure 11. Total, Correlated and Uncorrelated Errors, and Control Activity Versus Displays and Dynamics for the Main Experiment

As noted by the dashed lines the performance achieved in this experiment with K/s dynamics is somewhat better than that reported in Ref. 8. Furthermore, in the present study the pursuit display yielded about a 12 percent improvement (reduction) in error over the compensatory display, while Ref. 8 showed negligible differences or deteriorated performance with the pursuit display. However, these latter differences are within the variations to be expected among pilots versus nonpilots and for somewhat different controls and displays. Finally, the correlated error has the same trend between displays as the total error indicating that display format has little effect on remnant for K/s dynamics.

The performance obtained with K/s^2 dynamics is quite comparable between this study and Ref. 8 as shown in Fig. 11. It is interesting to note that comparing P versus C, the uncorrelated error for K/s^2 dynamics is lower for P while the correlated error is higher for P, the net result showing little difference in total error performance between the two display configurations. It is also noted that the uncorrelated error associated with the pursuit-plus-disturbance display was equal to that obtained with the compensatory display. Although the subjects claimed that the disturbance input was barely perceptible, it may have significantly affected the remnant portion of their output.

2. Describing Function Measurements

a. Compensatory Versus Pure Pursuit Display. Describing function data averaged over trials, subjects, and sessions are presented in Figs. 12 and 13. Both the measured error/input (E/I) and equivalent open-loop ($M/E = Y_\beta$) plots are given. The equivalent open-loop describing function data were computed from the measured average E/I data, as discussed in Appendix A. The details and results of analysis of variance of the E/I data are given in Appendix B. Describing functions for each subject are presented in Appendix C. In general, all subjects' data look similar and the mean data are truly representative of their typical behavior.

The describing function data for K/s dynamics in Fig. 12 show little difference in behavior between the pursuit and compensatory display modes

except for the low-frequency phase data. The compensatory display data exhibit the low frequency phase droop ("α-effect") typical of other human operator response measurements (Ref. 17). There appears to be negligible phase droop in the pursuit display data, however. Similar results are shown in Ref. 8. The low frequency phase droop characteristic in human operator describing functions has been measured and modeled quite extensively by McRuer, et al., (Ref. 6). More recently Elkind (Ref. 18) has shown that to some extent low frequency phase measurements can be biased by human operator induced remnant. The effect display format has on low frequency phase shifts is thus difficult to determine at this time.

The describing function data for K/s^2 dynamics given in Fig. 13 shows significant effects due to display mode. Greater low frequency error is incurred with the pursuit display. This is consistent with the performance measure results in which the correlated error was greater for the pursuit display. The corresponding equivalent open-loop describing functions show greatly attenuated gain and greatly reduced phase lags at low frequencies for the pursuit display. The ANOV in Appendix B shows these effects to be statistically significant at the two lowest measurement frequencies. The underlying pilot strategy is discussed later (p. 41).

b. Pursuit-Plus-Disturbance Inputs. The describing function measurements made during the pursuit-plus-disturbance tests are indicated by tagged symbols in Figs. 14 and 15. The measurements made at the mid-range pursuit frequencies generally correspond to the measurements obtained in the pure pursuit case. This indicates that pursuit behavior was not noticeably affected by the disturbance input and agrees with the subjects' subjective impression that the disturbance was barely perceptible.

The describing function measurement at the high disturbance frequency allows us to directly measure the crossover frequency obtained in closed loop operation on tracking error while using the pursuit display. The disturbance data in Figs. 14 and 15 show a regression in the error loop crossover frequency during pursuit tracking. The statistical significance of this result is discussed in Appendix B. Crossover frequency, phase margin,

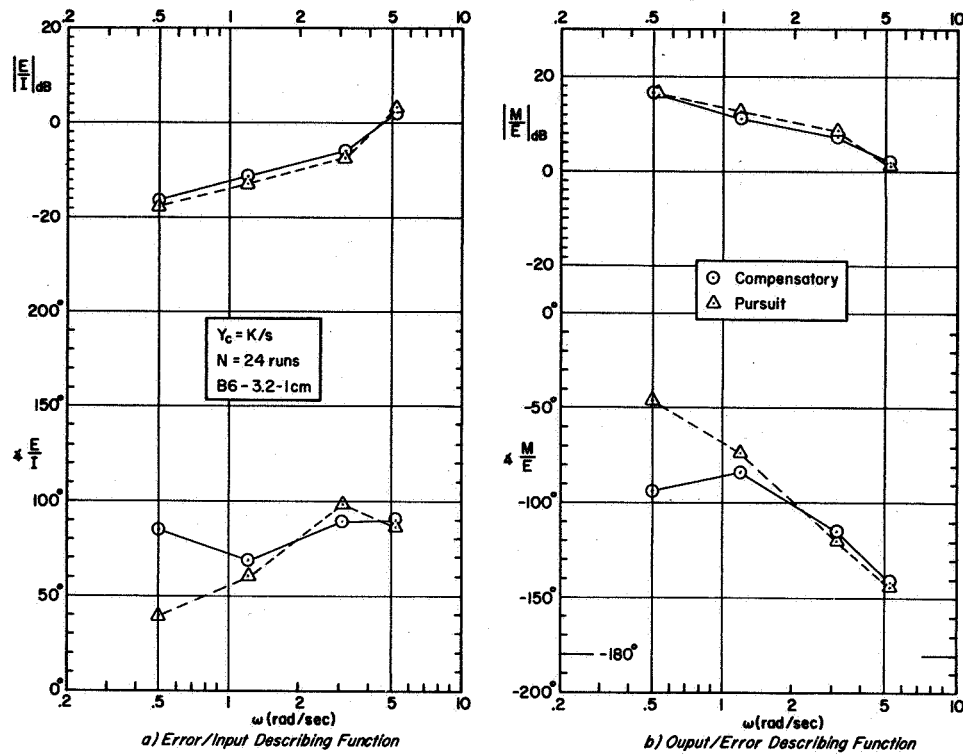


Figure 12. Mean Describing Functions with $Y_c = K/s$

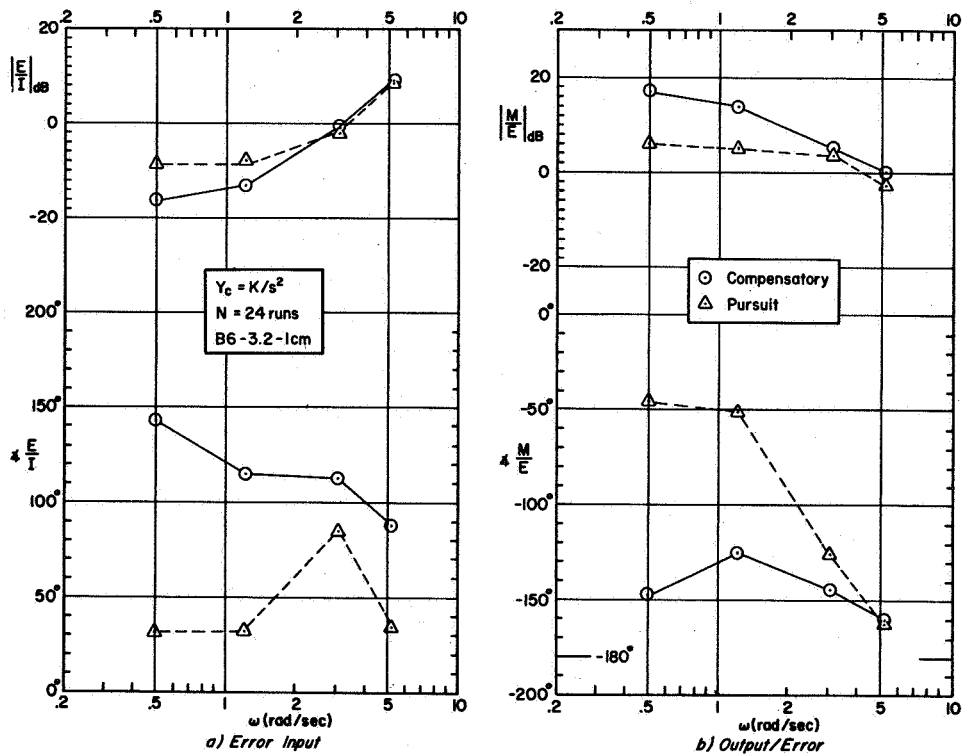


Figure 13. Mean Describing Functions with $Y_c = K/s^2$

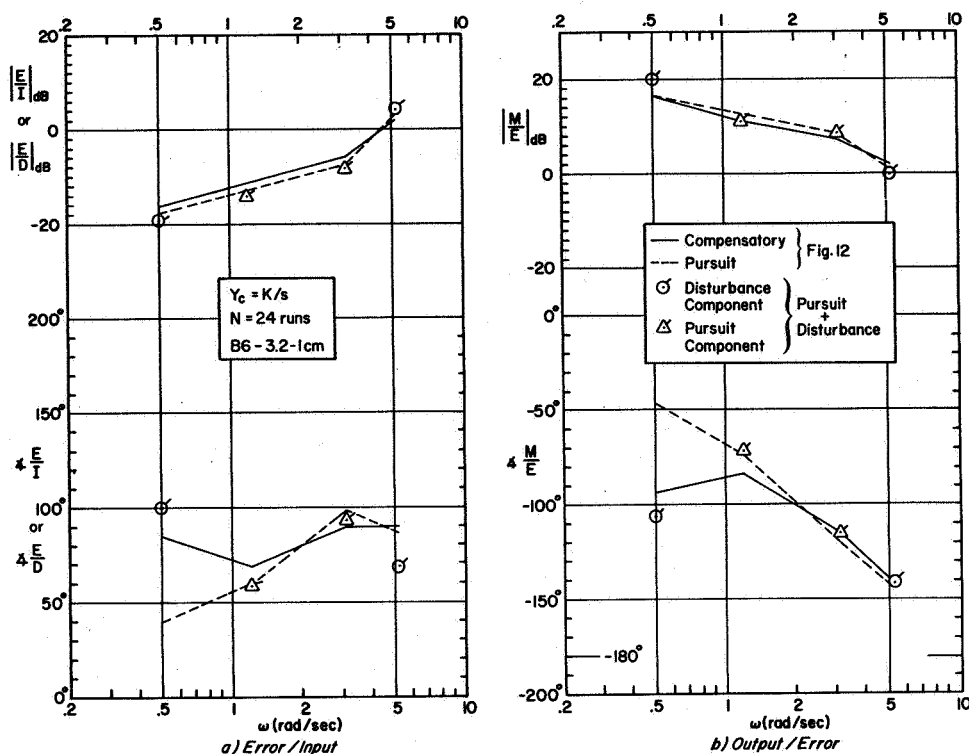


Figure 14. Comparison of Pursuit-Plus-Disturbance Data with Pure Pursuit and Compensatory Describing Functions; $Y_c = K/s$

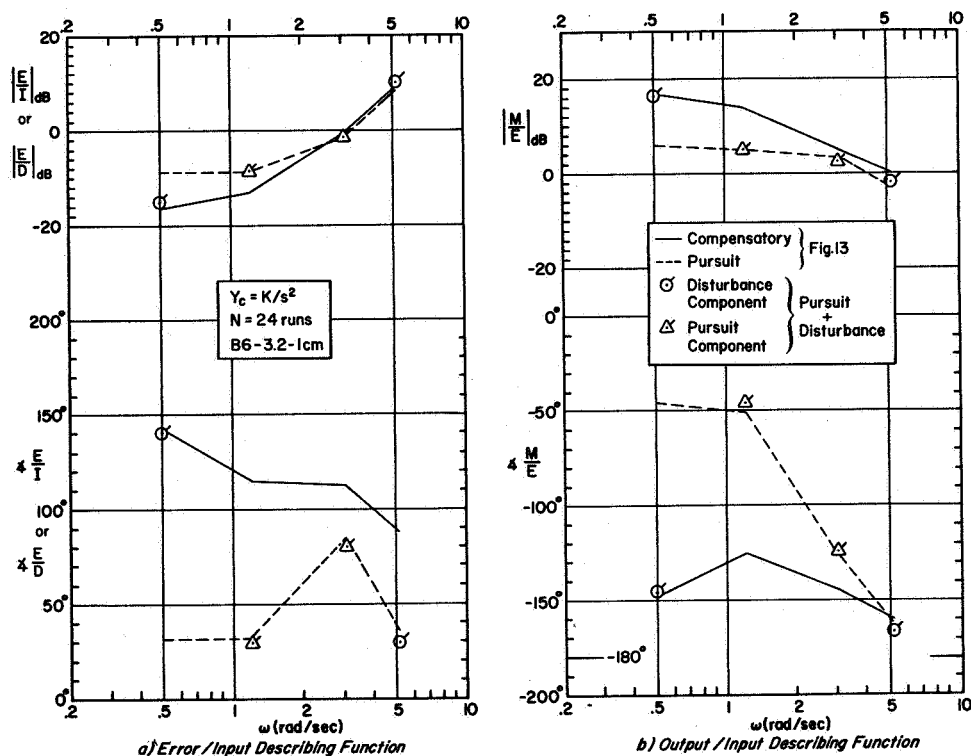


Figure 15. Comparison of Pursuit-Plus-Disturbance Data with Pure Pursuit and Compensatory Describing Functions; $Y_c = K/s^2$

and effective time delay at crossover is compared in Table VII for each of the display configurations and controlled element dynamics. Data derived from Ref. 8 are included in Table VII for comparison.* These data show that with a pursuit display the crossover frequency of the equivalent open-loop dynamics ($M/E = Y_\beta$) regresses about 20 to 25 percent from the level achieved with a compensatory display.

In Ref. 8 "implicit-pursuit model" describing functions were calculated, assuming that error response measured with a pure compensatory display could be applied to the error response portion of the pursuit model. The disturbance data shown here prove conclusively (for the first time) that an error control loop similar to the pure compensatory case does exist in pursuit tracking, but that it may be appreciably different in its parameters.

c. Closed-Loop Describing Functions. The closed-loop describing function gives the dynamic relationship between the system output, m , and the system forcing function, i . These two quantities are independently displayed to the operator by the pursuit display so that simple operations on either signal by the human operator should be revealed by the closed-loop describing functions, M/I .

The closed-loop describing functions, obtained from the E/I measurements as detailed in Appendix A, are given in Fig. 16. The K/s data show little difference between compensatory and pursuit displays. However, in the K/s^2 data the pursuit mode output is consistently attenuated (by nearly a factor of two) and lags the input at the dominant input frequencies by about 10 deg more than the compensatory mode. The closed-loop describing functions based on data given by Wasicko, et al., were computed for comparison purposes and are shown in Fig. 17. For both the K/s and K/s^2 dynamics the trends shown by the previous experiments

*The crossover frequencies and phase margins were approximated from hand faired curves passed through the data. The effective crossover time delays were calculated by assuming a crossover model and attributing all residual phase lag greater than 90 degrees to the equivalent time delay.

TABLE VII

CROSSOVER FREQUENCY, PHASE MARGINS AND EFFECTIVE TIME DELAYS

CONTROLLED ELEMENT (γ_c)	DISPLAY MODE	PRESENT STUDY $\omega_i = 3.2 \text{ rad/sec}$			WASICKO, et al (REF. 8)					
		$\omega_i = 2.5 \text{ rad/sec}$			$\omega_i = 4.0 \text{ rad/sec}$					
		ω_c (rad/sec)	ϕ_m	$\tau_e \omega_c$ (sec)	ω_c (rad/sec)	ϕ_m	$\tau_e \omega_c$ (sec)	ω_c (rad/sec)	ϕ_m	$\tau_e \omega_c$ (sec)
K/s	Compensatory	6.6	25°	0.17	5.7	16°	0.23	6.3	28°	
	Pure Pursuit	5.8	31°	0.18	5.2	20°	0.23	5.7	30°	
	Pursuit: Disturbance Measurement	5.2	33°	0.19	---	---	---	---	---	---
K/s ²	Compensatory	5.3	20°	0.23	5.0	8°	0.29	4.4	30°	0.24
	Pure Pursuit	4.2	32°	0.24	4.6	16°	0.28	3.7	43°	0.19
	Pursuit: Disturbance Measurement	4.0	22°	0.30	---	---	---	---	---	---

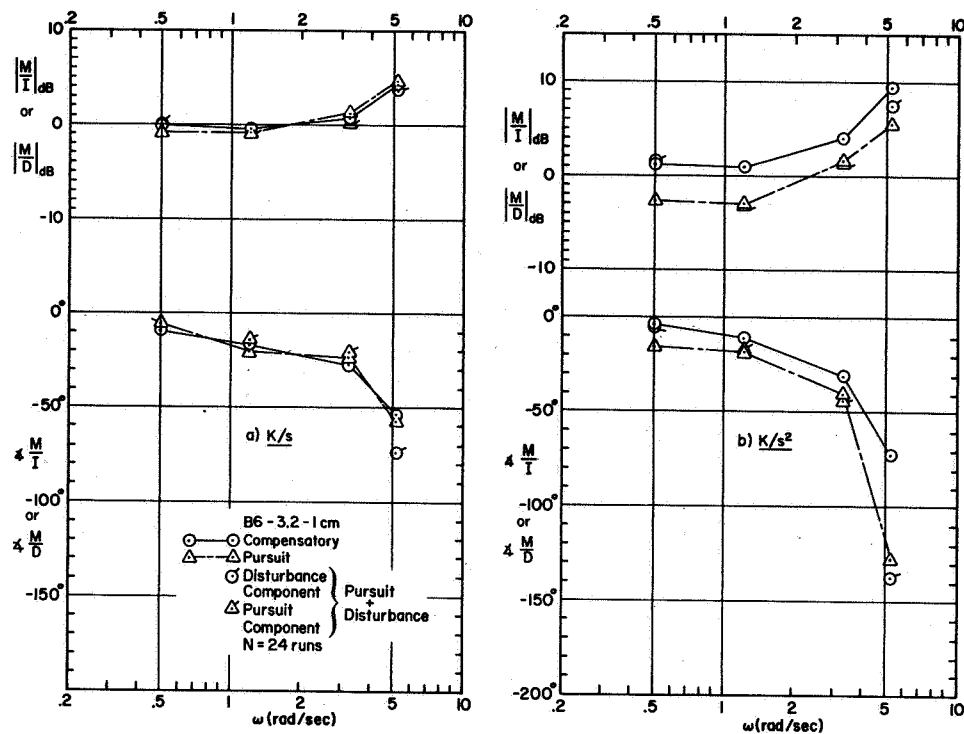


Figure 16. Mean Closed-Loop Describing Functions for Present Data

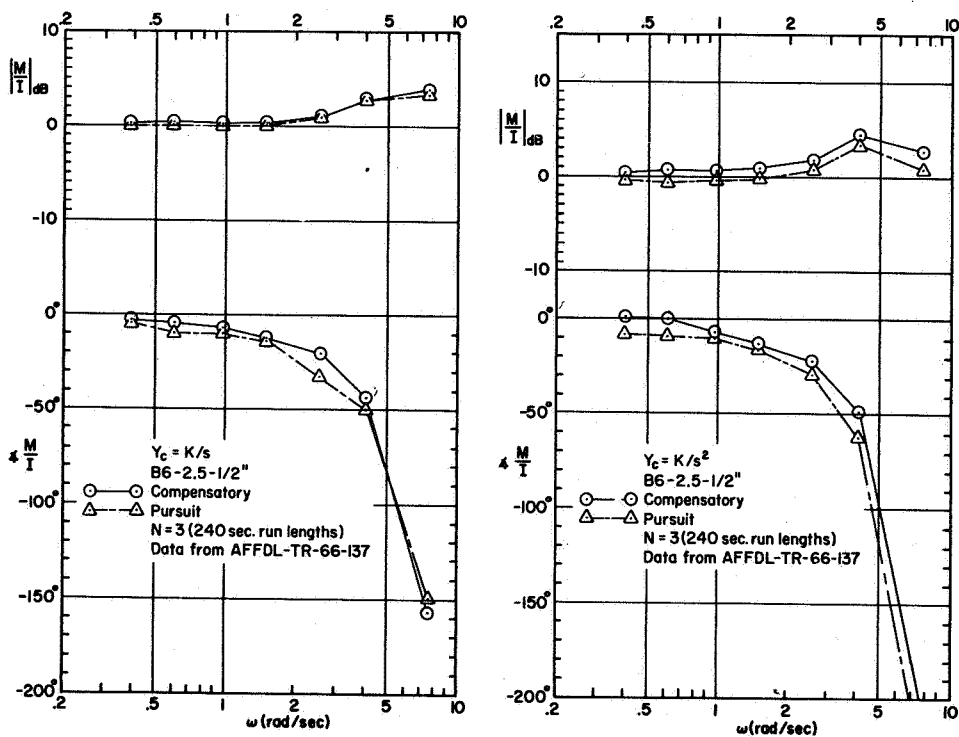


Figure 17. Mean Closed-Loop Describing Functions for Data from Ref. 8

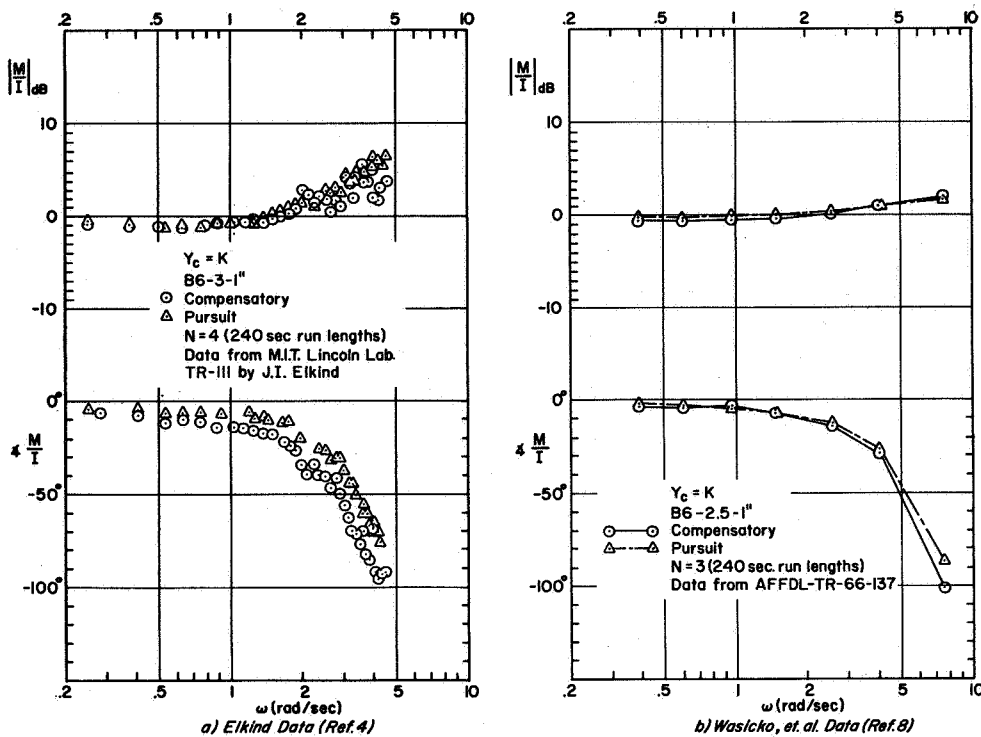


Figure 18. Comparison of Closed-Loop Describing Functions for $Y_C = K$ Data from Refs. 4 and 8

are similar to those mentioned above for our data. For completeness closed-loop describing functions for Wasicko's pure-gain controlled element ($Y_C = K_C$) data were also computed and are compared with Elkind's $Y_C = K_C$ data for a comparable input spectrum (Ref. 4) in Fig. 18.

An overall comparison of the plots presented in Figs. 16, 17, and 18 reveals the following observations:

$Y_C = K_C$ Tracking with the pursuit display gives less closed-loop phase lag than tracking with a compensatory display. Elkind's data shows greater phase lag reduction for the pursuit display than does the data of Wasicko, et al. This may be due to the control device used in his experiments; a light weight, finger manipulated stylus. Wasicko, et al., employed a spring-restrained sidestick operated by wrist rotation which would introduce significant arm neuromuscular dynamics into the loop.

$Y_c = K_c/s$ No consistent differences in closed-loop response are apparent between the compensatory and pursuit displays. Our data does show greater phase lag and less amplitude peaking for the high frequency disturbance input, however. As suggested previously for the open-loop describing functions, this result could mean that the error tracking loop operates with lower bandwidth during pursuit tracking than it does during compensatory tracking.

$Y_c = K_c/s^2$ Tracking with the pursuit display gives a large and uniform (-6 to -8 dB) attenuation at all frequencies and greater phase lag (by about 10 deg at the lowest three measurement frequencies) than for the compensatory display. The Wasicko, et al, data show the same trends but with lesser increments. The manipulator used herein was operated with the fingertips, in a fore and aft direction, as opposed to the wrist rotation required by Wasicko's manipulator, so that neuromuscular effects might account for the different gain and phase increments observed in the two experiments.

During the experiment the subjects remarked that to avoid overshooting during pursuit tracking, they attempted to keep the follower (i.e., the symbol representing the system output m) between the input and the fixed reference line. This strategy would account for the constant attenuation shown for the K_c/s^2 data.* No simple explanation has yet been found for the observed phase differences.

Analytical modeling and curve fitting of the pursuit data was deferred in anticipation of further experimental investigation of input predictability from this program and analytical results from an associated program.

3. Pilot Questionnaire

At the end of the experiment the pilots were asked to fill out a questionnaire dealing with their subjective impressions of the various experimental tasks. The questions and pilots' replies are given in Table VIII.

Also shown in Table VIII is the implication which would be drawn from the actual scores shown in Fig. 11.

*Eppler (Ref. 19) has obtained similar results for $Y_c = K_c$ dynamics.

TABLE VIII
SUMMARY OF REPLIES TO PILOTS' QUESTIONNAIRE

QUESTION	Y_c	INDIVIDUAL PILOT'S REPLIES				NET CONSENSUS	IMPLICATIONS OF DATA	
		1	2	3	4		Relevant Measure	Implied Preference
a. Which display was easiest to use?	K/s K/s ²	C P	C C	C P	P P	C P	Control Activity (lower $\overline{ c }$):	P ÷ C P
b. Which display required closer attention?	K/s K/s ²	P P	C P	C C	P P	(Split) P	(None?)	— —
c. Which display gave least error (subjectively)?	K/s K/s ²	P P	C C	P P	P P	P P	Total Error (lower e^*):	P P ÷ C
d. Was the added information of the pursuit display helpful?	K/s K/s ²	Neutral Somewhat	Somewhat deleterious Somewhat	Very Very	Somewhat Somewhat	(Split) Yes	Remnant Error (lower e_n^*):	(Split) Yes
e. As an overall impression which display mode was best?	(Combined)	P	C	P	P	P	(None)	—
f. Was the disturbance input noticeable?	K/s K/s ²	Slightly Slightly	No No	Slightly Slightly	Slightly Slightly	Slightly Slightly	Relative Disturbance Error (σ_{ed}/σ_{ei})†:	0.35 0.30

†Relative disturbance error is the ratio between the correlated components of error at the disturbance and command input frequencies.

The pilots were not familiar with rating scales, so only simple comparisons were asked for between the compensatory and pursuit display modes. There are obviously various possible meanings for the terms used in these questions. However, the questions were framed in the terms used by the pilots themselves during the experiments in order to formalize their candid remarks as simply as possible.

The consensus was not unanimous for any question but the following trends were indicated (C = compensatory display; P = pursuit display):

K/s C was easier to use, but P gave subjectively less error. Opinion was mixed on which display required closer attention, and whether the added information in the pursuit display was helpful. The disturbance input was only slightly noticeable, mainly because the low-frequency component that dominated od , was greatly suppressed by the time it appeared as a closed-loop error component.

K/s^2 P was easier to use than C and, subjectively, gave less error than C, but also required closer attention. The presence of the disturbance was barely noticeable.

As an overall impression, three of the four pilots preferred the pursuit display.

Correlation of various objective measures (and the superiority of P versus C implied by them) with the subjective evaluations reveals reasonable agreement, wherever relevant measures are available. For example the significantly lower control activity noted in the data for the K/s^2 with pursuit display is reflected in the pilot's "easier-to-use" evaluation. However the strong consensus that C is easier to use with K/s dynamics is not supported by the $|c|$ scores, and so there may be more to this term subjectively than just control activity. Error evaluations are certainly related to total error (e^*) scores, yet the $P \doteq C$ result for K/s^2 dynamics seems to conflict with the subjective consensus. However, closer inspection of the individual ratings and scores shown previously in Fig. 10 reveals that only one pilot is in conflict on an individual basis, as shown below for the K/s^2 case:

PILOT NUMBER	1	2	3	4	AVERAGE
Least e^* , subjectively	P	C	P	P	P
Lower e^* , measured (Fig. 10)	C	C	P	P	$P \div C$

If the addition of the separately visible command input in the pursuit case was considered helpful, this could be reflected in a lower remnant component. The data on e_n^* bear out the subjectively split opinion for the K/s dynamics and agreed on the helpfulness of P with K/s^2 dynamics.

No objective correlate for attentional demand was found for this single axis, continuously fixated task. Gross neuromuscular tension level is suspected as an attentional stress indicator, but it was not measured. The effective neuromuscular time delay, τ_e , is related to muscle tension level (Ref. 20), but the values for τ_e shown in Table VII were only evaluated at crossover frequency and showed insufficient variation to yield sensitive indications.

Finally, the overall preference for the pursuit display is obviously a compound evaluation based on all of the foregoing factors, weighted in some unknown manner. No attempt was made to seek a cost function of weighted scores and parameters which would correlate with the overall display ratings, because these results only scratch the surface of the problem. The fairly good consistency among these four pilots gives encouragement for more subjective/objective comparisons of this type, to seek better questions, find more relevant objective measures, and to confirm their correlation with subjective impressions.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

In general, the validation data obtained in this investigation correlates well with previous results (e.g., from Wasicko, et al, Ref. 8), thus corroborating most of the "anomalous" results found therein. The major conclusions drawn from the present study and past research are as follows:

1. The four instrument rated pilot/subjects showed good consistency in their asymptotically learned behavior, as measured by the performance measure and describing function results.
2. The pilots quickly achieved stationary performance levels with K/s dynamics and their total error scores (e^*) and control activity ($|c|$) were similar. The pilots had greater difficulty with the K/s^2 dynamics, however. They required considerable practice to achieve stationary performance levels and individual data differed more than for the K/s dynamics.
3. The total error scores did not show any significant difference between compensatory (C) and pursuit (P) displays. However, for K/s^2 dynamics the control activity was significantly higher for the compensatory display. The results indicate that total error scores are not a sensitive measure of pursuit behavior.
4. The describing function measures clearly differentiated between pursuit and compensatory behavior. For the equivalent open-loop describing function $|Y_B(j\omega) = M(j\omega)/E(j\omega)|$, the pursuit display indicates less low-frequency phase lag by the pilot than for the compensatory display. For K/s^2 dynamics a pursuit display gives comparatively less low-frequency amplitude ratio, a lower crossover frequency, and more phase margin than C. In general, the describing function measurements show a greater number of differences between pursuit and compensatory behavior than the performance scores.

5. The use of a separate nondisplayed "disturbance" input, uncorrelated with the primary "command" input, permitted the independent measurement and verification of compensatory action by the pilot in a pursuit display situation. Comparison of the pursuit-plus-disturbance (P+D) describing function data with pure P and C data shows that:
 - a. Pilot pursuit behavior was little affected by the disturbance input. Pilot comments indicated the errors resulting from the disturbance were barely noticeable.
 - b. An error loop closure does exist during pursuit situation, as postulated in Ref. 5. However this closure has a somewhat lower crossover frequency and greater phase margin than for a purely compensatory display.
6. A comparison of previous and present closed-loop describing functions for pursuit versus compensatory tracking with K, K/s, or K/s² dynamics revealed the following trends:
 - a. $Y_C = K$. The pursuit display gives lower overall closed-loop phase lag and near-unity amplitude ratio.
 - b. $Y_C = K/s$. The pursuit display gives smaller phase lag at low frequencies.
 - c. $Y_C = K/s^2$. The pursuit display adds a nearly constant increment to the phase lag and results in significantly more attenuation in the output relative to the command.
7. The closed-loop describing functions clearly reveal the consistent undershoot of the system output, $m(t)$, relative to the command input, $i(t)$, with P for K/s² dynamics, which account for an increase in the input-correlated portion of the tracking error. The pilots remarked during the experiment that they were using this strategy to minimize overshooting. This effect was also found in the data of Ref. 8.
8. The pilots' subjective evaluation of their performance, their "effort," and attentional demands of the task agreed roughly with relevant performance measurements. However, although the total error scores were not significantly different between P and C, three of the four pilots preferred P.

Finally, we conclude that the equipment, measurement techniques, pilots, and tie-in data base are adequate to proceed with more advanced experiments.

B. RECOMMENDATIONS

1. The pursuit-plus-disturbance input measurement scheme works and should be exploited further. More frequencies and different levels should be investigated in order to fill in the unknown blocks of the command-disturbance matrix previously given in Table I, Section II of this report.
2. Explanations should be sought for the observed effects of display mode on pilot describing functions, particularly the increase in amplitude attenuation and phase lag for the closed-loop pursuit response as controlled element order increases. These effects may be due to the pilot's attempt to predict the short term course of the input; therefore, further research should be devoted to a set of inputs with graded predictability.
3. Mathematical models, such as those of Elkind (Ref. 4), McRuer (Ref. 8), and Eppler (Ref. 19) should be refined and fitted to the combined data from this study and the recommended experimental work.

Experiments to resolve some of these questions are currently under way.

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APPENDIX A

PERFORMANCE AND DYNAMIC RESPONSE MEASUREMENTS

Performance scores and dynamic response measurements were calculated on an analog computer during each tracking trial. Logic was set up on the computer to start data measurement 20 sec after the beginning of a trial and end at 120 sec, thus giving a 100 sec measurement period.

PERFORMANCE MEASURES

The absolute value of the error signal was integrated over the 100 sec measurement period to give a raw error score. The ratio of this raw error score to the value of the absolute integrated input signal was used as the error performance score:

$$e^* = \frac{\overline{|e|}}{\overline{|i|}} = \frac{\int_0^{100} |e(t)| dt}{\int_0^{100} |i(t)| dt} \quad (A-1)$$

The average controller action score was obtained by properly scaling the integrated absolute value of controller output:

$$\overline{|c|} = \int_0^{100} |c(t)| dt \quad (A-2)$$

DESCRIBING FUNCTION MEASURES

The tracking-loop forcing function was composed of the sum of nine cosine waves:

$$i = \sum_i A_i \cos \omega_i t \quad \text{for } i = 1, \dots, 9 \quad (A-3)$$

Also available were the individual unit amplitude waveforms

$$\cos \omega_1 t \text{ and } \sin \omega_1 t$$

These signals allowed the real and imaginary parts of the error to unit input (\hat{i}) cospectrum (Φ_{ie}) to be calculated during the measurement period using the relationships

$$\Phi_{ie}(\omega) = \text{Re}\Phi_{ie} + i\text{Im}(\Phi_{ie})$$

$$\text{where } \text{Re}(\Phi_{ie})_i = \int_0^{100} \cos \omega_1 t \cdot e(t) dt \quad (A-4)$$

$$\text{and } \text{Im}(\Phi_{ie})_i = \int_0^{100} \sin \omega_1 t \cdot e(t) dt$$

The $\text{Re}(\Phi_{ie})_i$ and $\text{Im}(\Phi_{ie})_i$ data at each of four measurement frequencies were recorded at the end of each trial along with the raw performance scores.

The error/input describing function was calculated off-line with the aid of a G-15 digital computer. The A_1 from Eq. A-1 were known, and the gain and phase of E/I were computed using the relationships

$$\left| \frac{E}{I} \right|_i \text{ dB} = 10 \log \frac{\text{Re}^2(\Phi_{ie})_i + \text{Im}^2(\Phi_{ie})_i}{A_1^2/2} \quad (A-5)$$

$$\angle \left(\frac{E}{I} \right)_i = \tan^{-1} \frac{\text{Im}(\Phi_{ie})_i}{\text{Re}(\Phi_{ie})_i}$$

Given the error input describing function the equivalent open-loop and closed-loop describing functions were calculated from the relationships

$$Y_{\beta} = \frac{M}{E} = \left(\frac{E}{I} \right)^{-1} - 1 \quad (A-6)$$

and

$$\frac{M}{I} = 1 - \frac{E}{I} \quad (A-7)$$

where Y_{β} , E/I , and M/I are complex numbers.

The variability in the M/E calculations due to variability in E/I data is illustrated in Fig. A-1. Representative data were used and the standard deviation of $|E/I|^{-1}$ and $\angle(E/I)^{-1}$ was derived from the analysis of variance tables given in Appendix B. The magnitudes of $(E/I)^{-1}$ and M/E are comparable for each measurement frequency, which results in comparable variability between the two measures.

CORRELATED ERRORS

The correlated mean square error is given by

$$\overline{e_I^2} = \sum_i (\Phi_{ee})_i \quad (A-8)$$

where

$$\Phi_{ee} = \left| \frac{E}{I} \right|^2 \Phi_{ii}$$

$|E/I|$ was known at the four measurement frequencies, and approximated at the remaining six input frequencies. At nonmeasurement input frequencies E/I was calculated from $|E/I|_{dB}$ approximations obtained by linear interpolation. The interpolation scheme is illustrated graphically in Fig. A-2 for representative data. The peak of the $|E/I|_{dB}$ curve was assumed to occur at the 5.15 rad/sec input frequency, and it was also assumed that $|E/I|_{dB} = 0$ dB (ratio = 1.0) at the 13.13 rad/sec input component. The assumptions for the shelf region should not seriously affect the correlated error calculation as shown in the Φ_{ee} plot in Fig. A-3, since the shelf contribution to correlated mean square error is small.

The total mean square error was calculated by assuming the error signal was Gaussian, so that

$$\overline{e^2} = \frac{\pi}{2} \overline{|e(t)|^2} \quad (\text{A-9})$$

where $\overline{|e(t)|^2}$ was calculated on-line. The uncorrelated or remnant error was obtained from the relation

$$\overline{e_n^2} = \overline{e^2} - \overline{e_I^2} \quad (\text{A-10})$$

The error components were normalized to the mean-square value of the input, and the total, correlated and uncorrelated, normalized error components obtained from the relations

$$e^* = \left(\frac{\overline{e^2}}{\overline{i^2}} \right)^{1/2}$$

$$e_I^* = \left(\frac{\overline{e_c^2}}{\overline{i^2}} \right)^{1/2}$$

$$e_n^* = \left(\frac{\overline{e_n^2}}{\overline{i^2}} \right)^{1/2}$$

For some of the K/s controlled element runs the relative remnant error e_n^* was quite small, and occasionally a negative estimate was obtained for $\overline{e_n^2}$. In these cases $\overline{e_n^2}$ was set equal to zero, and the correlated error component was assumed to be equal to the total error ($e_I^* = e^*$).

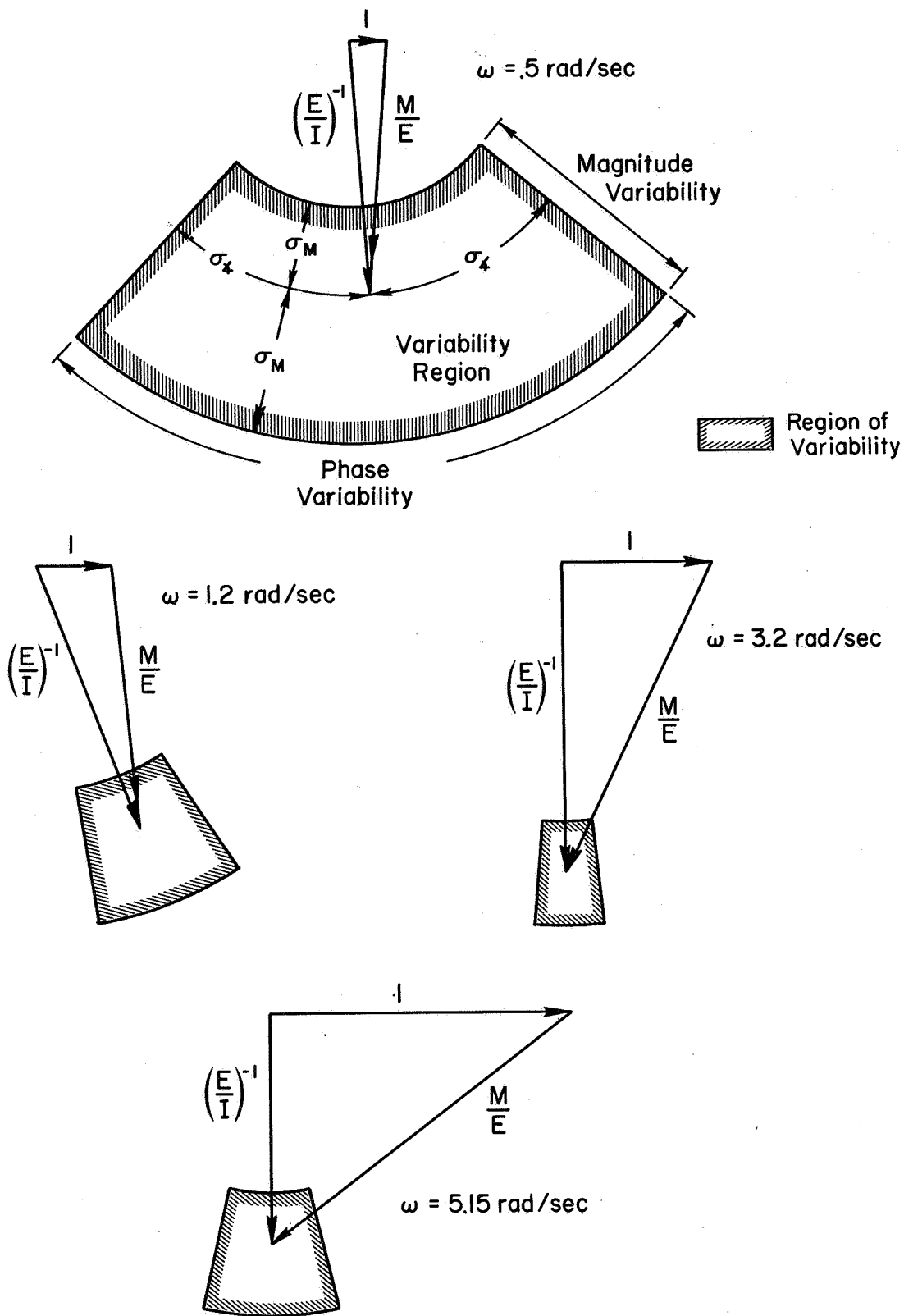


Figure A-1. Vector Relationships and Variability Zones

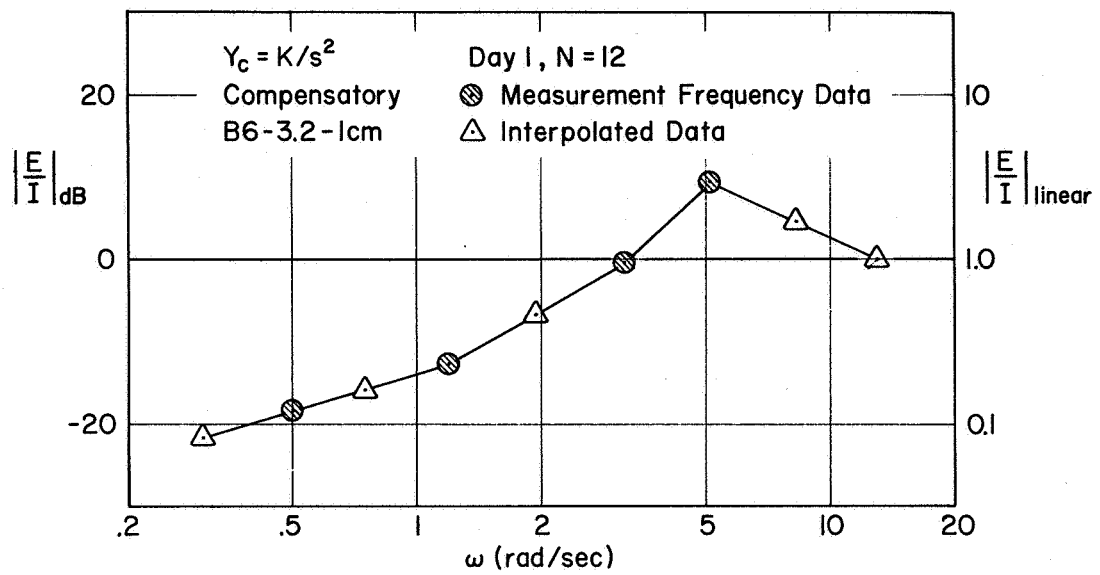


Figure A-2. Interpolation Scheme for E/I

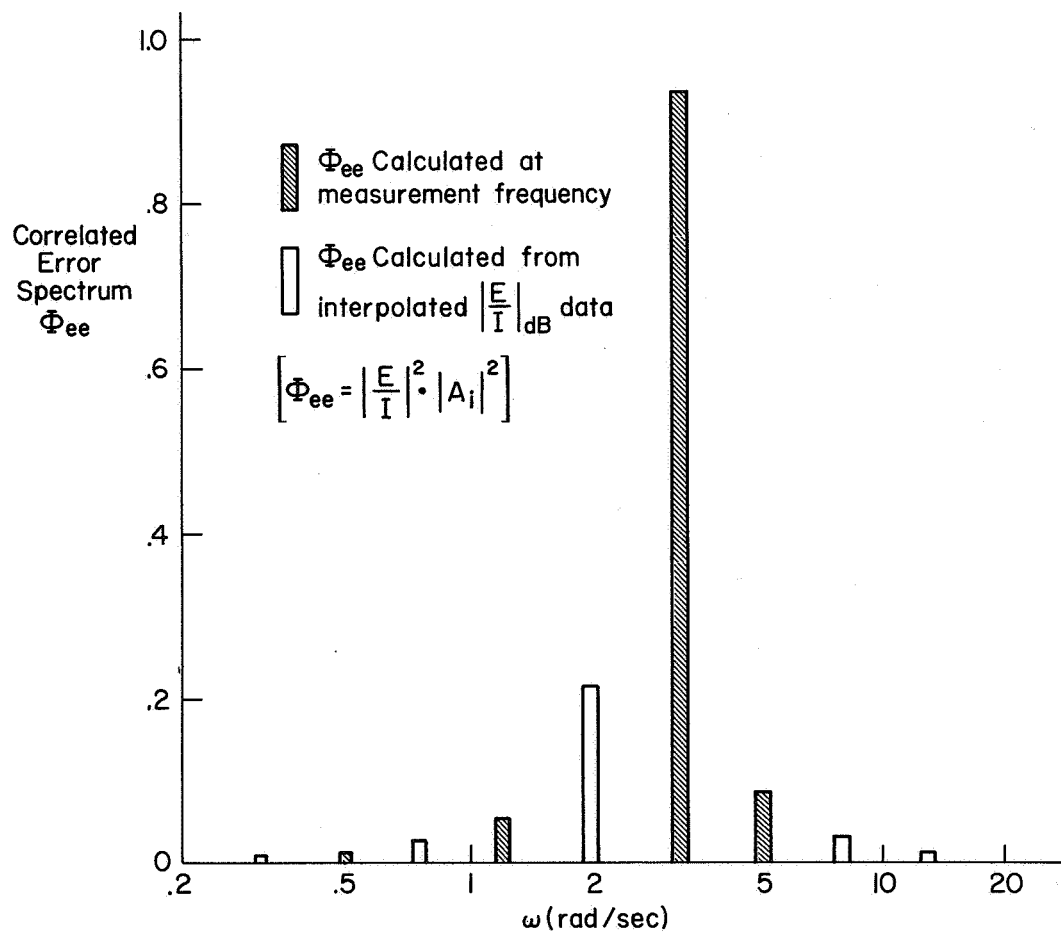


Figure A-3. Resulting Error Spectrum

APPENDIX B

ANALYSIS OF VARIANCE

The performance scores and describing function measurements were analyzed by analysis of variance (ANOV) procedures in order to assess the statistical significance of mean differences in the averaged data. The experiment was set up in a complete factorial design with three replications per condition. In the ANOV model pilots were considered a random variable since they were arbitrarily selected. The other variables were assumed to be fixed.

Separate ANOV were performed on each of the performance scores, e^* , e_c^* , e_n^* , and $|c|$. For the describing function measurements a separate ANOV was performed on the magnitude and phase of (E/I) at each measurement frequency. Separate ANOV were performed at each frequency because each frequency measurement is independent of all others, and the variability of the data varied significantly between the measurement frequencies. Both theory and experience has shown (e.g., see McRuer, et al., Ref. 17) that the variability is high for low-frequency measurements and reaches a minimum near crossover frequency for standard input spectra.

PERFORMANCE MEASURES ANOV

The ANOV results for the performance measures are given in Tables B-I through B-IV. A summary of the significance levels is given in Table B-V. The main results are that display mode had a significant effect only on the uncorrelated (remnant-induced) error (Table B-III) and on controller output (Table B-IV). Performance differences between pilots were highly significant, and, as would be expected, the controlled element dynamics had significant effect on performance also.

In the total error (e^*) ANOV all two-way interactions involving pilots were highly significant. These effects are evident in the plot of total error cell-means given in the text (Fig. 10). The pilot-by-controlled element and pilot-by-display interactions for e_c^* were also highly significant.

TABLE B-I

* ANOV
e

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUMS OF SQUARES	MEAN SQUARES	F RATIO
Session (S)	1	0.00795	0.00795	0.748
Pilot (P)	3	0.36199	0.12066	80.4***
Y _c (Y)	1	4.08377	4.08377	116**
Display (D)	2	0.01138	0.00569	0.284
SP	3	0.03185	0.01062	7.08***
SY	1	0.00058	0.00058	0.332
SD	2	0.00094	0.00047	0.0869
PY	3	0.10552	0.03517	23.5***
PD	6	0.11764	0.01961	13.05***
YD	2	0.02443	0.01222	2.17
SPY	3	0.00540	0.00180	1.2
SPD	6	0.03248	0.00541	3.6**
SYD	2	0.00028	0.00014	0.023
PYD	6	0.03380	0.00563	3.75**
SPYD	6	0.03647	0.00608	4.06**
Within replicates, σ	96	0.14427	0.00150	
Total	143	4.99875		

*0.05 level of significance

**0.01 level of significance

***0.001 level of significance

TABLE B-II

e_I^{*} ANOV

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUMS OF SQUARES	MEAN SQUARES	F RATIO
Session (S)	1	0.02377	0.02377	11.3 [*]
Pilot (P)	3	0.25895	0.08632	39.5 ^{***}
Y _c (Y)	1	1.94370	1.94370	64.8 ^{**}
Display (D)	2	0.00296	0.00148	0.0755
SP	3	0.00631	0.00210	0.964
SY	1	0.00016	0.00016	0.113
SD	2	0.00201	0.00100	0.221
PY	3	0.08985	0.02995	13.75 ^{***}
PD	6	0.11772	0.01962	9 ^{***}
YD	2	0.07027	0.03514	5.94 [*]
SPY	3	0.00426	0.00142	0.651
SPD	6	0.02713	0.00452	2.07
SYD	2	0.00127	0.00063	0.0842
PYD	6	0.03545	0.00591	2.71 [*]
SPYD	6	0.04496	0.00749	3.43 ^{**}
Within replicates, σ	96	0.20960	0.00218	
Total	143	2.83835		

*0.05 level of significance

**0.01 level of significance

***0.001 level of significance

TABLE B-III

* ANOV

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUMS OF SQUARES	MEAN SQUARES	F RATIO
Session (S)	1	0.01361	0.01361	0.352
Pilot (P)	3	0.15605	0.05202	7.65***
Y _c (Y)	1	2.75560	2.75560	460***
Display (D)	2	0.07068	0.03534	5.16*
SP	3	0.11589	0.03863	5.68**
SY	1	0.00234	0.00234	0.134
SD	2	0.00508	0.00254	0.201
PY	3	0.01801	0.00600	0.884
PD	6	0.04103	0.00684	1.01
YD	2	0.04325	0.02163	3.06
SPY	3	0.05750	0.01917	2.83*
SPD	6	0.07595	0.01266	1.86
SYD	2	0.00115	0.00058	0.0563
PYD	6	0.04233	0.00706	1.04
SPYD	6	0.06185	0.01031	1.52
Within replicates, σ	96	0.65207	0.00679	
Total	143	4.11240		

*0.05 level of significance

**0.01 level of significance

***0.001 level of significance

TABLE B-IV

 $\sqrt{c(t)}$ | ANOV

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUMS OF SQUARES	MEAN SQUARES	F RATIO
Session (S)	1	60.42471	60.42471	4.58
Pilot (P)	3	82.79277	27.59759	3.33*
Y _c (Y)	1	874.18778	874.18778	44.6**
Display (D)	2	3157.68750	1578.84375	149***
SP	3	39.65932	13.21977	1.59
SY	1	0.00188	0.00188	0.0843 × 10 ⁻³
SD	2	6.22423	3.11212	0.363
PY	3	58.82053	19.60684	2.36
PD	6	63.81244	10.63541	1.28
YD	2	1896.31139	948.15570	29.7***
SPY	3	66.80834	22.26945	2.69
SPD	6	51.47859	8.57976	1.03
SYD	2	14.41208	7.20604	0.643
PYD	6	191.44725	31.90788	3.85**
SPYD	6	67.15968	11.19328	1.35
Within replicates, σ	96	796.70140	8.29897	
Total	143	7427.92990		

*0.05 level of significance

**0.01 level of significance

***0.001 level of significance

TABLE B-V

PERFORMANCE MEASURES ANOV SUMMARY

SOURCE OF VARIATION	EFFECTS ON:			
	e^*	e_c^*	e_n^*	$\overline{ c }$
SIGNIFICANT AT LEVEL:				
Session (S)	—	0.05	—	—
Pilot (P)	0.001	0.001	0.001	0.05
Y_c (Y)	0.01	0.01	0.001	0.01
Display (D)	—	—	0.05	0.001
SP	0.001	—	0.01	—
SY	—	—	—	—
SD	—	—	—	—
PY	0.001	0.001	—	—
PD	0.001	0.001	—	—
YD	—	0.05	—	0.001
SPY	—	—	0.05	—
SPD	0.01	—	—	—
SYD	—	—	—	—
PYD	0.01	0.05	—	0.01
SPYD	0.01	0.01	—	—

Definition of terms:

— = Not significant
 0.05 = Probably significant
 0.01 = Significant
 0.001 = Very significant

The display-by-controlled-element interaction (YD) in the $\overline{|c|}$ analysis was highly significant, which is primarily due to the high control activity associated with K/s^2 dynamics and the compensatory display, as seen in Fig. 10 of the text. Otherwise the $\overline{|c|}$ interactions are small, reflecting the peculiar constancy of $|c|$, as discussed in the text.

DESCRIBING FUNCTION ANOV

The ANOV results for the describing function measures are given in Tables B-VI through B-XIII. The significance levels are summarized in Table V-XIV.

Table B-VI shows that display mode had a significant effect on the E/I phase angle near crossover, but not on the magnitude there. The vector calculation illustrated in Fig. B-1 shows that the differences in (E/I) phase data between compensatory and disturbance inputs result in a lower open-loop amplitude ratio $(|M/E|_{dB})$ for the disturbance input. This verifies the assertion in the text that compensatory behavior during pursuit display tracking shows a regression in crossover frequency over the open-loop response achieved with a compensatory display.

The display format significantly affected low-frequency phase lag as shown in Table B-XIV despite the large residual errors in the phase ANOV (Tables B-X and B-XI). This substantiates the finding in the text that the pursuit display lessens the low-frequency phase droop or "α-effect."

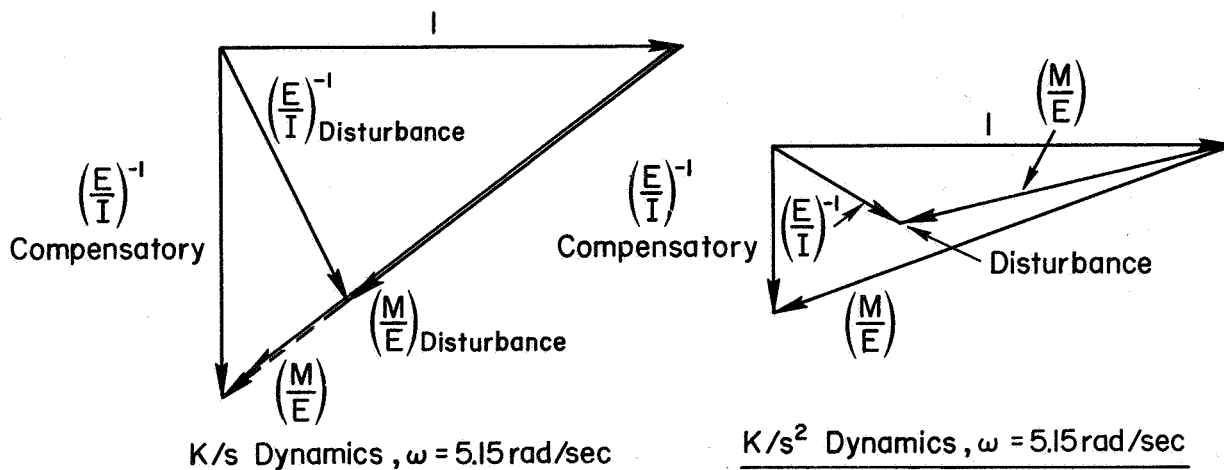


Figure B-1. $E/I \rightarrow M/E$ Vector Calculations

TABLE B-VI

 $|E/I|_{\omega} = 0.5$ ANOV

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUMS OF SQUARES	MEAN SQUARES	F RATIO
Session (S)	1	2.80004	2.80004	156**
Pilot (P)	3	145.84802	48.61601	3.07*
Y _c (Y)	1	648.04188	648.04188	16.2*
Display (D)	2	485.89344	242.94672	12.3**
SP	3	0.05393	0.01798	0.00114
SY	1	33.83361	33.83361	13.1*
SD	2	12.74864	6.37432	0.992
PY	3	120.28957	40.09652	2.53
PD	6	118.23356	19.70559	1.24
YD	2	402.86160	201.43080	17.8**
SPY	3	7.72812	2.57604	0.163
SPD	6	38.58295	6.43049	0.407
SYD	2	62.85740	31.42870	5.69*
PYD	6	67.71975	11.28663	0.715
SPYD	6	33.14237	5.52373	0.349
Within replicates, σ	96	1513.95727	15.77039	
Total	143	3694.59216		

*0.05 level of significance

**0.01 level of significance

***0.001 level of significance

TABLE B-VII

 $|E/I|_{\omega} = 1.2$ ANOV

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUMS OF SQUARES	MEAN SQUARES	F RATIO
Session (S)	1	3.75391	3.75391	0.152
Pilot (P)	3	186.79862	62.26621	14***
Y _c (Y)	1	202.89628	202.89628	23.1*
Display (D)	2	124.50338	62.25169	4.98
SP	3	74.19901	24.73300	5.56**
SY	1	0.90408	0.90408	0.174
SD	2	21.13066	10.56533	0.956
PY	3	26.38782	8.79594	1.98
PD	6	74.76950	12.46158	2.81*
YD	2	288.92028	144.46014	37.7***
SPY	3	15.56814	5.18938	1.17
SPD	6	66.32349	11.05392	2.5*
SYD	2	5.55221	2.77610	0.185
PYD	6	22.89732	3.81622	0.861
SPYD	6	89.70661	14.95110	3.38**
Within replicates, σ	96	425.95000	4.43698	
Total	143	1630.26133		

*0.05 level of significance

**0.01 level of significance

***0.001 level of significance

TABLE B-VIII

 $|E/I|_{\omega} = 3.2$ ANOV

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUMS OF SQUARES	MEAN SQUARES	F RATIO
Session (S)	1	41.92562	41.92562	3.46
Pilot (P)	3	157.51007	52.50336	24.8***
Y_c (Y)	1	1093.29422	1093.29422	64.5**
Display (D)	2	33.06945	16.53473	1.24
SP	3	36.15371	12.05124	5.72**
SY	1	0.79507	0.79507	0.0958
SD	2	6.08388	3.04194	0.9
PY	3	50.70926	16.90309	7.97***
PD	6	80.04560	13.34093	6.28***
YD	2	10.98303	5.49151	2.24
SPY	3	24.85761	8.28587	3.91*
SPD	6	20.28677	3.38113	1.59
SYD	2	1.79293	0.89646	0.237
PYD	6	14.70374	2.45062	1.16
SPYD	6	22.66414	3.77736	1.78
Within replicates, σ	96	203.29667	2.11767	
Total	143	1798.17177		

*0.05 level of significance

**0.01 level of significance

***0.001 level of significance

TABLE B-IX

 $|E/I|_{\omega} = 5.15$ ANOV

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUMS OF SQUARES	MEAN SQUARES	F RATIO
Session (S)	1	2.88434	2.88434	6.13
Pilot (P)	3	26.87364	8.95788	1.69
Y _c (Y)	1	1350.56250	1350.56250	56.7**
Display (D)	2	50.89954	25.44977	0.775
SP	3	1.40795	0.46932	0.0885
SY	1	21.16000	21.16000	1.93
SD	2	53.54831	26.77415	2.09
PY	3	71.33268	23.77756	4.49**
PD	6	196.66717	32.77786	6.18***
YD	2	12.77363	6.38681	0.661
SPY	3	32.96638	10.98879	2.08
SPD	6	76.54534	12.75756	2.41*
SYD	2	25.44018	12.72009	9.21*
PYD	6	58.06222	9.67704	1.83
SPYD	6	8.27064	1.37844	0.26
Within replicates, σ	96	509.04367	5.30254	
Total	143	2498.43818		

*0.05 level of significance

**0.01 level of significance

***0.001 level of significance

TABLE B-X

$$\lambda(E/I)_{\omega} = 0.5 \text{ ANOV}$$

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUMS OF SQUARES	MEAN SQUARES	F RATIO
Session (S)	1	979.95085	979.95085	0.732
Pilot (P)	3	5530.73951	1843.57984	0.837
Y _c (Y)	1	55897.17467	55897.17467	24.7*
Display (D)	2	305372.22999	152686.11499	139***
SP	3	4008.38676	1336.12892	0.608
SY	1	785.26050	785.26050	0.408
SD	2	7989.11803	3994.55901	0.493
PY	3	6771.90800	2257.30267	1.03
PD	6	6614.59857	1102.43310	0.5
YD	2	62193.83540	31096.91770	23.2**
SPY	3	5767.08912	1922.36304	0.873
SPD	6	2723.07647	453.84608	0.206
SYD	2	16201.61101	8100.80550	12.9**
PYD	6	8067.77637	1344.62940	0.608
SPYD	6	3753.69899	625.61650	0.284
Within replicates, σ	96	210735.05827	2195.15686	
Total	143	703391.51251		

*0.05 level of significance

**0.01 level of significance

***0.001 level of significance

TABLE B-XI

 $\chi^2 (E/I)_{\omega} = 1.2$ ANOV

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUMS OF SQUARES	MEAN SQUARES	F RATIO
Session (S)	1	56.38758	56.38758	0.0431
Pilot (P)	3	4860.90967	1620.30322	10.3***
Y _c (Y)	1	487.85766	487.85766	3.84
Display (D)	2	66574.88787	33287.44394	123***
SP	3	3918.29750	1306.09917	8.3***
SY	1	0.04951	0.04951	0.895 × 10 ⁻³
SD	2	583.42368	291.71184	1.28
PY	3	379.78777	126.59592	0.804
PD	6	1628.71466	271.45244	1.71
YD	2	43115.86503	21557.93252	52.7***
SPY	3	165.80974	55.26991	0.35
SPD	6	1366.27748	227.71291	1.44
SYD	2	440.14661	220.07331	1.46
PYD	6	2459.34395	409.89066	2.59*
SPYD	6	863.68346	143.94724	0.912
Within replicates, σ	96	15134.76460	157.65380	
Total	143	142036.20677		

*0.05 level of significance

**0.01 level of significance

***0.001 level of significance

TABLE B-XII

 $\lambda (E/I)_{\omega} = 3.2$ ANOV

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUMS OF SQUARES	MEAN SQUARES	F RATIO
Session (S)	1	670.11951	670.11951	1.86
Pilot (P)	3	10907.38436	3635.79479	119***
Y _c (Y)	1	16.36202	16.36202	0.0257
Display (D)	2	5272.07304	2636.03652	2.05
SP	3	1080.37267	360.12422	11.8***
SY	1	259.42471	259.42471	1.19
SD	2	37.76644	18.88322	0.1
PY	3	1914.41324	638.13775	20.9***
PD	6	7716.33823	1286.05637	42.3***
YD	2	10893.66752	5446.83376	41.3***
SPY	3	655.18302	218.39434	7.15***
SPD	6	1137.79661	189.63277	6.23***
SYD	2	97.26454	48.63227	0.486
PYD	6	789.21332	131.53555	4.33***
SPYD	6	601.95790	100.32632	3.29**
Within replicates, σ	96	2925.94067		
Total	143	44975.27780	30.47855	

*0.05 level of significance

**0.01 level of significance

***0.001 level of significance

TABLE B-XIII

 $\lambda (E/I)_{\omega} = 5.15$ ANOV

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUMS OF SQUARES	MEAN SQUARES	F RATIO
Session (S)	1	270.13662	270.13662	0.45
Pilot (P)	3	11159.42262	3719.80754	22.5***
Y _c (Y)	1	35277.91758	35277.91758	15.1*
Display (D)	2	38744.24971	19372.12485	21**
SP	3	1798.87434	599.62478	3.64*
SY	1	5.14155	5.14155	0.0109
SD	2	171.23797	85.61898	0.985
PY	3	7008.13112	2336.04371	14.2***
PD	6	5536.14184	922.69031	5.59***
YD	2	16401.60226	8200.80113	20**
SPY	3	1413.04958	471.01653	2.85*
SPD	6	521.38800	86.89800	0.527
SYD	2	1257.57383	628.78692	0.945
PYD	6	2458.00807	409.66801	2.48*
SPYD	6	3995.33852	665.88975	4.03**
Within replicates, σ	96	15866.46133	165.27564	
Total	146	141884.67495		

*0.05 level of significance

**0.01 level of significance

***0.001 level of significance

TABLE B-XIV
DESCRIBING FUNCTION ANOV SUMMARY

SOURCE OF VARIATION	EFFECTS ON:							
	$ E/I _{dB}$				$\Delta E/I$			
	$\omega = 0.5$	$\omega = 1.2$	$\omega = 3.2$	$\omega = 5.15$	$\omega = 0.5$	$\omega = 1.2$	$\omega = 3.2$	$\omega = 5.15$
	SIGNIFICANT AT LEVEL:				SIGNIFICANT AT LEVEL:			
Session	0.01	—	—	—	—	—	—	—
Pilot	0.05	0.001	0.001	—	—	0.001	0.001	0.001
Y_c	0.05	0.05	0.01	0.01	0.05	—	—	0.05
Display	0.001	0.05	—	—	0.001	0.001	—	0.01
SP	—	0.01	0.01	—	—	0.001	0.001	0.05
SY	0.05	—	—	—	—	—	—	—
SD	—	—	—	—	—	—	—	—
PY	—	—	0.001	0.01	—	—	0.001	0.001
PD	—	0.05	0.001	0.001	—	—	0.001	0.001
YD	0.01	0.001	—	—	0.01	0.001	0.001	0.01
SPY	—	—	0.05	—	—	—	0.001	0.05
SPD	—	0.05	—	0.05	—	—	0.001	—
SYD	0.05	—	—	0.05	0.01	—	—	—
PYD	—	—	—	—	—	0.05	0.001	0.5
SPYD	—	0.01	—	—	—	—	0.01	0.01

Definition of terms:

— = Not significant
 0.05 = Probably significant
 0.01 = Significant
 0.001 = Very significant

APPENDIX C

INDIVIDUAL PILOT DESCRIBING FUNCTIONS

The E/I and M/E describing functions of each pilot for each controlled element with compensatory and pursuit display modes are illustrated in Figs. C-1 through C-4. It is noted from the individual describing functions that the pursuit display leads to less error response ($|E/I|$) variability among the subjects. This effect is statistically significant, as shown in Appendix B, Table B-XIV, where the pilot/display (PD) interaction was significant for $|E/I|$ at the three highest measurement frequencies.

In general, the form of the four pilots' describing functions was quite consistent. This lends some validity to the mean describing functions obtained by averaging over pilots.

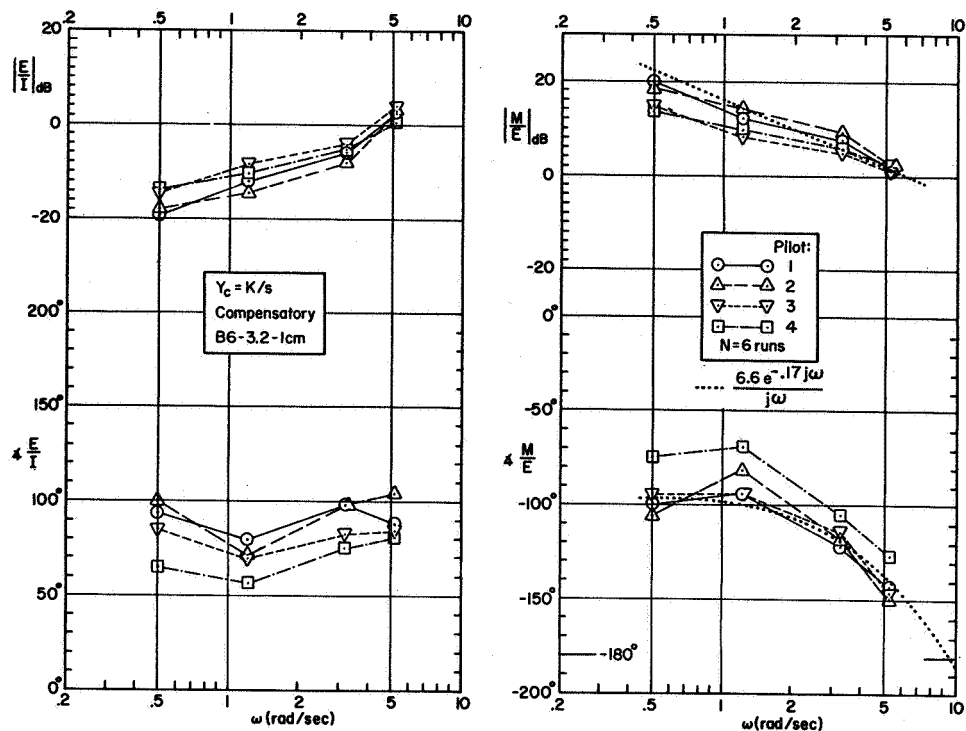


Figure C-1. Individual Pilot Describing Functions for K/s Dynamics and a Compensatory Display

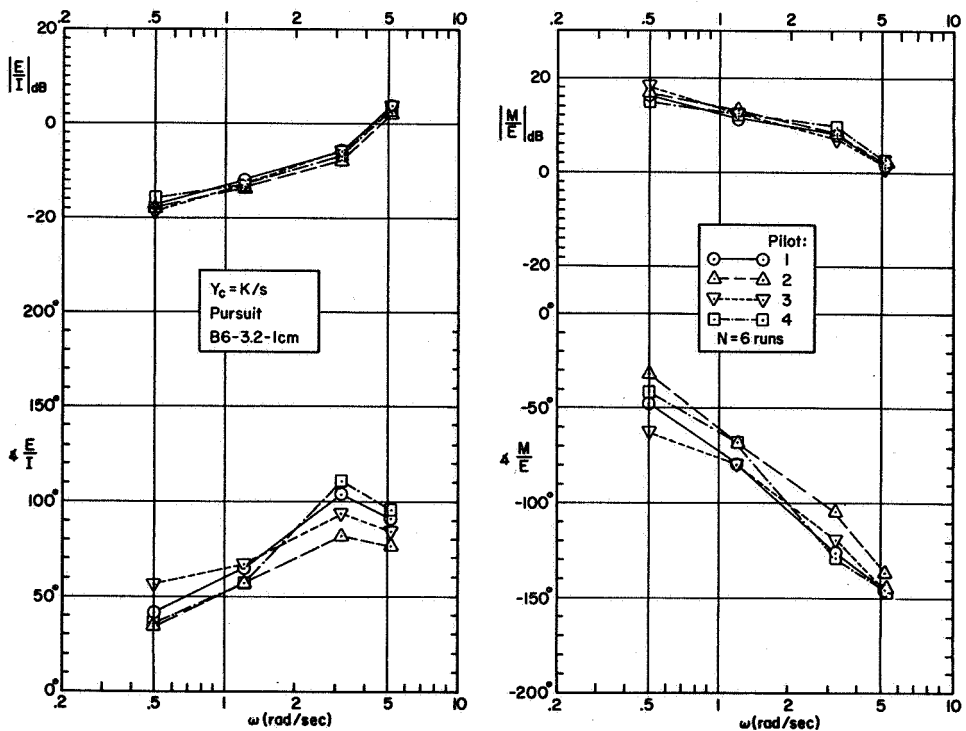


Figure C-2. Individual Pilot Describing Functions for K/s Dynamics and a Pursuit Display

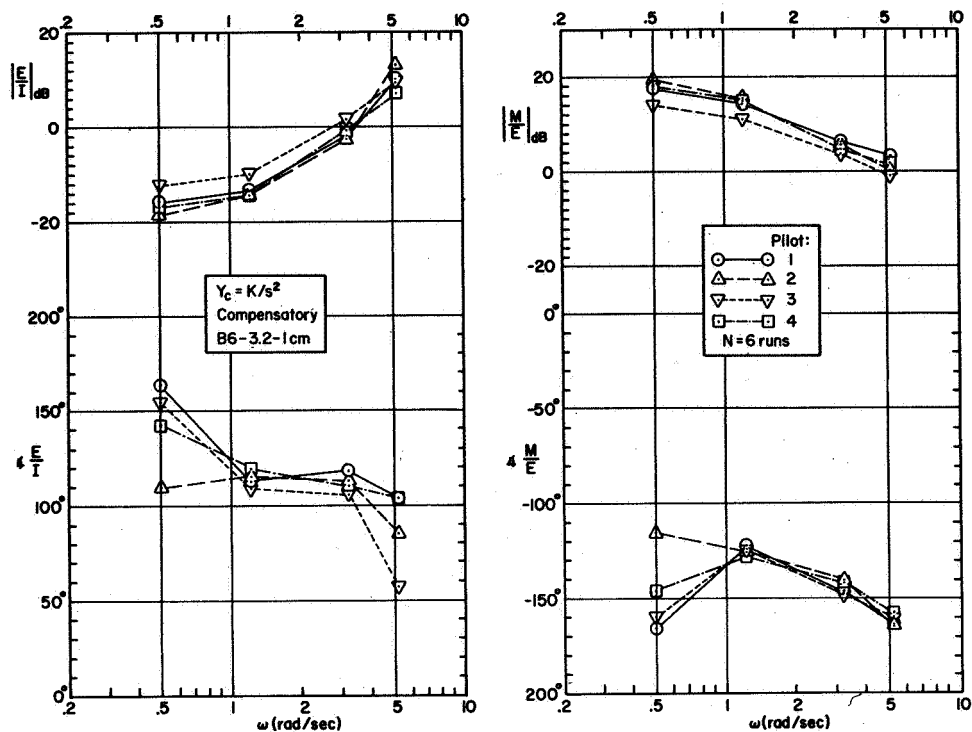


Figure C-3. Individual Pilot Describing Functions for K/s^2 Dynamics and a Compensatory Display

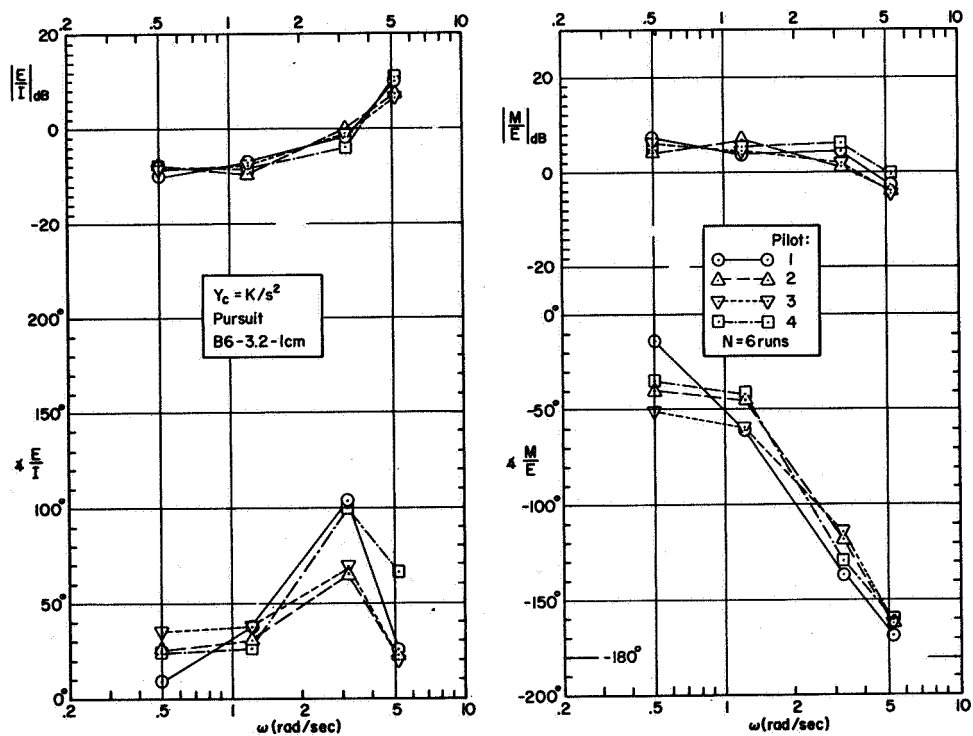


Figure C-4. Individual Pilot Describing Functions for K/s^2 Dynamics and a Pursuit Display

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